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THE DETERMINATION, ASSESSMENT, AND DESIGN OF 'IN-STREAM VALUE' STUDIES FOR THE NORTHERN GREAT PLAINS REGION

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THE DETERMINATION, ASSESSMENT, AND DESIGN OF "IN-STREAM VALUE" STUDIES

For The Northern Great Plains Region

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For The Northern Great Plains Region

FINAL REPORT

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September 1, 1974

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PREFACE

This document has been prepared in fulfillment of Contract #68-01-2413, issued by Region 8 of the U.S. Environmental Protection Agency, to the Geology Department, University of Montana, Missoula, Montana.

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ABSTRACT

An extensive literature review was conducted to determine the discharge requirements of various components of a warm water fishery. Where exact hydrologic parameters were not measured directly in individual studies, they were estimated from inferred statements and knowledge of hydrologic variables leading to certain instream conditions. From this information it was possible to determine which components of the stream community would be most seriously affected by reduced discharges.

In addition, a number of different methods used in the recommendation of minimum streamflows were reviewed. These methods were evaluated for their reliability and ease of use. It was concluded that a method for recommending minimum discharges should not sacrifice reliability for expediency.

A methodology is proposed for the recommendation of minimum discharges for a warm water fishery. This method utilizes field measurements of critical stream areas and biological criteria determined from the use of indicator species. For large rivers, migration and spawning requirements are analyzed using the paddlefish (Polyodon spathula) as the indicator species. For smaller rivers, the suggested indicator species is the sauger (Stizostedion canadense). Rearing flows are determined on the basis of stream productivity by analyzing macroinvertebrate habitats, and on the basis of fish habitat typing. The indicator species for determining adequate fish habitat is the stonecat (Notorus flavus).

A number of variables were identified which might require a greater amount of in-stream flow than the fishery, per se. These variables included streamflow needs for riparian and other sub-irrigated vegetation, water quality parameters, anchor ice formation, and the relationship between discharge and sediment yield. Information concerning these variables is insufficient at this time to determine whether a variable will "over-ride" the streamflow requirement for the fishery itself. Further research is needed in these areas, and several investigative methods for conducting such research are proposed.

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INTRODUCTION

> "Techniques for determining stream flow recommendations which we have tested might be classified into four basic categories: those which apply field measurements; techniques which employ a variety of conversion factores; techniques which involve field observation and the application of judgement; and those methods based on various formulas. For those who appreciate the jargon, they are more simply the "Gurley," the "Slide Rule," the "Eye-Ball," and the "Crystal Ball" techniques.....There are two fundamental differences in these techniques--those employed behind a desk are easy; those in the field are reliable."
>
> Kenneth Thompson, in the Proceedings of the Instream Flow Requirement Workshop, Portland, Oregon, March 15-16, 1972.

The problem of determining discharge needs for maintaining the integrity of a stream ecosystem is being studied by many government and private agencies. The methods currently being employed usually fall into the very appropriate classifications given by Thompson in the quote above. Each type of methodology has its own strengths and weaknesses. Methods which provide biologically reliable information generally are expensive in terms money, manpower, and time. Those which take little time, money, or manpower may be unreliable and difficult to defend.

The primary target of consideration in flow requirement studies is the question of stream discharge. Stated as simply as possible, the question is: "How much of a stream's discharge may be considered excess?" A project developer is usually interested in the amount of water available for off-stream use. Naturally, the project developer wants to devote as much water as possible to purposes which pay for the project. As a consequence, the biologist is under considerable pressure to determine the minimum discharge which will maintain the stream resource. This approach frequently results in maintaining a mere vestige of the former aquatic resources (Fraser, 1971). The number of variables which should be considered by the biologist in making his recommendation complicates his decision. As a result, there is often considerable friction between the engineering-oriented developer and the biology-oriented researcher. There are situations in biology which have no engineering analogs, and may be unfamiliar, if not unknown, to the engineer. Therefore, the developer may feel that the flow recommended by the biologist is much in excess of what really needs to be left in the stream. The biologist may fear that the same recommended flow is too conservative, and too much water is being removed.

In-stream flow refers to the amount of water which is set aside and is not available for development. It is water left in the river for beneficial use by fish and wildlife, and for consideration of water quality, recreation, and esthetic requirements. As a beneficial use, in-stream water is a demand which must compete with other uses, such as irrigation or industrial withdrawal. The demand for water by large coal-electric generating stations and coal gasification plants is substantial. A large number of such conversion plants is the Northern Great Plains region would represent a tremendous demand for a limited supply of water. The exact water requirements for a large scale development of the coal resources in the Northern Great Plains have not been set, but volumes on the order of 2.6 million acre feet per year have been suggested as available for industrial use in Montana and Wyoming (Gibbs, 1972).

Thus, the methodology used for final decisions on a flow requirement recommendation must be as accurate and reliable as possible so that interested parties may be reconciled to the discharge(s) recommended.

Most of the in-depth flow methodologies originate on the west coast. Agencies in California, Oregon, and Washington extensively utilize field measurements of hydrologic parameters at different discharges, coupled with comprehensive physical requirements for each species of fish at different phases of its life history. However, on the west coast, the economic importance of the anadromous fishery has resulted in a considerable body of knowledge of the streamflow needs of the important species. No method has yet been devised specifically for recommending minimum flows in a warm-water fishery, primarily because the requirements of warm-water species have not been organized and promulgated as flow-related criteria (Thompson, 1972). Warm-water fisheries are also more complex than are cold water fisheries. For example, where a cold-water fishery might have 10 species of fish, most of which are closely related, a warm-water fishery might have 35 or more species, many of which are not closely related.

The difference between a cold-water and a warm-water fishery is not well defined in many streams in the Northern Great Plains. Theoretically, this difference is defined by the maximum summer water temperature, but is also affected by the duration of this summer maximum and by the productivity of the stream. A stream dominated by trout is easily defined as being a cold-water stream, while one dominated by largemouth bass and bullheads can be described as typically a warm-water fishery. However, many streams in this region contain both cold-water and warm-water species. This probably indicates that such streams lie on the borderline between cold- and warm-water fisheries. Conditions are thus marginal for many species under the natural flow regime of the streams, and may be extremely sensitive to any changes in that flow regime. In addition, this borderline zone probably moves up and down the river during the course of a year, as temperatures or other conditions become seasonally unfavorable for one group or the other.

To clarify some of the interrelationships that exist in a stream ecosystem, Giger (1973) has categorized those factors influencing stream fishes into three principal components: hydrogeographic, chemical, and biotic. The hydrogeographic component includes such channel geometry characteristics as gradient (slope), bed roughness (size and shape of bottom materials and their resistance to current), meander (sinuosity of the channel), channel shape, and other perameters , as well as discharge related characteristics such as area, current velocity, depth and width. The chemical component might include aspects of water quality such as turbidity, waste assimilation capacity, toxicity of minor elements, and dissolved oxygen. Temperature is also characterized as a chemical component. The biotic component includes such broad categories as primary production, ecology of stream invertebrates, aquatic and shoreline vegetation, and ecology of fishes. The biotic component can be extremely important in warm-water fisheries because of the greater number of species, and the increased complexity of the food web.

The specific purpose of this study is the synthesis of a methodology which can be used in establishing the minimum flow requirements for streams with primarily warm-water fish communities in the Northern Great Plains of the United States. In order to meet this objective, an exhaustive literature search was conducted to determine: (1) methods in current use, the concepts involved, and the strengths and weaknesses of each method type; and (2) the discharge-related physical requirements, water quality tolerances, and biological factors which affect species distributions and abundances in warm-water communities. Several methods were reviewed, each with varying degrees of difficulty and reliability, and are presented in this study. However, for some of the methodologies presented, the data base is lacking certain critical information. This information must be measured before these methodologies can be used. It is believed that this data will not be difficult to obtain. It has simply never been measured before, for lack of any substantial motivation related to important long term problems. The motivation now exists.

SUMMARY

Several methodological frameworks have been investigated. Some methods rely on field measurements and biological criteria. Others rely on field observation and professional judgement which is generalized to apply to a wide variety of streams. Some methods estimate the amount of streamflow excess in terms of statistical treatments of the streamflow records. Methods which rely on field measurements and biological criteria are considered to give more reliable results, and are therefore more easily defended than other methods. Methods which do not use field measurements are more expedient and less costly, but may be unreliable when applied to streams with high seasonal variation of flow.

Flow recommendations must consider each phase of the life history of all species inhabiting a river. It is reasoned that if the life requirements for the most sensitive species are met, then the requirements for all other species will also be met. Biological criteria for the detailed data methods are defined for migration, spawning, and rearing. These criteria have been measured for many of the salmonids, but because of the complexity of warm-water communities, or for lack of motivation, these criteria have never before been established for a warm-water community. The most sensitive species, those with the most stringent physical requirements during any single phase of the life cycle, have been defined by this study. These species are considered "indicator species", with different indicators used for different aspects of the life history. The criteria for an indicator species are: (1) the species must demonstrate a very narrow range of physical requirements during

the phase for which it is the indicator; and (2) it must be naturally present in the area to which its biological requirements are applied.

For large river systems, the suggested migration and spawning indicator species is the paddlefish (Polyodon spathula). For smaller streams in which the paddlefish does not spawn, the recommended migration and spawning indicator species is the sauger (Stizostedion canadense).

The recommended rearing flow indicator species is the stonecat (Notorus flavus), which appears to have the most limiting physical requirements. This species is selected for its stringent velocity requirements, its narrow habitat range, and its sensitivity to sedimentation.

The recommendation of rearing flows is a difficult task, because in a warm-water community there are two distinct aspects to rearing. These are productivity and balance. Productivity refers to the capability of the stream to produce fish biomass and is strictly a quantitative term. Balance refers to the microhabitat requirements of the indicator species, and the ability of the stream to maintain a diversified fish community. (Technically, the same stream flow should be optimum for both productivity and balance, but this concept has never been tested.)

The proposed methodology uses the "Usable Width Method" as developed by the Oregon Fish Commission, for the determination of recommended migration discharges. In large rivers where the paddlefish is the indicator species, the migration flow is taken to be the required spawning flow as well. The discharge required for paddlefish migration is initiated during sauger spawning to provide suitable conditions for early spawning sauger and walleye, and should be maintained for at least three months to ensure the successful spawning of northern pike (Esox lucius).

All other field measurements utilize the graphical approach developed for determining the spawning requirements for salmonids by the Washington Department of Fisheries and the U.S. Geological Survey. This method does not require site randomization, and can use fewer cross-sections than does any other method to obtain statistical validity. Results may be produced on planimetric maps, which are more tangible and easier to understand during explanation and defense of a recommended flow. A major criticism of this method is that it is restricted to rivers which can be waded. However, under this approach field measurements are made in shallow water areas. Thus, the small-river limitation of the detailed data method has been partially solved.

The concept of an "over-riding consideration" is introduced in this study. An over-riding consideration is some factor which presents an in-stream flow requirement in excess of the demand by the indicator species at a given time. One example of an over-riding consideration might be a discharge required for recharge of bank storage to maintain riparian vegetation, which is higher than the migrational requirements of the migration flow indicator species. Other over-riding considerations might be a discharge requirement for maintaining water quality, which is higher than the required rearing discharge of the rearing indicator species, or a discharge during winter months which maintains normal ice conditions. At certain times of the year, riffle productivity may be the over-riding consideration for rearing flows, while at other times of the year, the physical requirements of the rearing flow indicator species may be paramount.

CONCLUSIONS

The specific physical requirements for many warm-water fish species have not been measured directly. These requirements can, however, be inferred from life history studies, habitat typing, and distributional studies. Many species are restricted to a certain bottom type, which reflects certain ranges of hydrologic conditions. However, because substrate is a function of velocity, depth, and slope for a given area, inferred velocities as they appear in the text should be considered approximate.

Because some species have very restrictive physical requirements and others do not, it is important that streamflows meet the requirements of the most sensitive species. Nearly every effect of reduced streamflow favors generalist species, such as carp, buffalo, white suckers, bullheads, and catfish. These species, especially the carp, have the capability of becoming dominant in the system, eventually replacing other, more desireable game or food species.

Several factors were discovered which may require a higher discharge than that required by the most sensitive, or "indicator" species. These factors were termed over-riding considerations. Potentially over-riding considerations include: recharge requirements for riparian or other sub-irrigated vegetation, maximum water temperatures, frequency of anchor ice formation, dissolved oxygen concentrations, and sediment transport capacity of the river.

The flow recommendation methodology presented in this study does not now have a complete data base from which to work. Information concerning the passage requirements and migration stimuli for paddlefish is lacking. Nor can the study determine which factors will be over-riding considerations. Further research is required to determine these factors. However, much of the information needed for the operation of the method will not be overly difficult to obtain. Data base requirements can probably be met within a year or two.

Further research is also needed for the determination of the over-riding considerations. For some of the water quality parameters, such as dissolved oxygen requirements, this will require a prediction of the future waste loading of streams to be dewatered.

RECOMMENDATIONS

The proposed methodology should be field tested, and results from the field testing compared with the recommended flows given by both the Montana method and the Bureau of Sport Fisheries and Wildlife method.

Biological criteria as developed in the text are only approximate, and should be measured or defined for those species classified as indicator species. Additionally, other sensitive species should also be studied to determine their potential use as indicator species.

The determination of the over-riding considerations is of great importance. It is, at this time, unclear which factor presents the greatest water demand at a given time of the year. Suggested research areas include: the determination of bank recharge requirements during spring runoff, modeled water quality parameters including temperature and dissolved oxygen, frequency of anchor ice formation as a function of depth and velocity, and sediment transport-discharge equilibrium relationships.

Finally, after the discharge recommendations have been made, it is strongly recommended that permanent transects be established across rivers to be dewatered. These surveyed transects should be included in the Vigil Network System of the U.S. Geological Survey. The expressed purpose of these cross sections is the monitoring of the channel morphology for the detection of aggradation, while remedial action is still possible.

STREAM HYDROLOGY

A stream is a dynamic entity. Several concepts in stream hydrology have evolved, since the beginning of this century, to describe and explain the characteristics of flowing water and its relationship to its channel and drainage basin. These concepts have direct bearing on the problem of the constancy and stability of stream ecosystems and will be explored in some detail.

William Morris Davis was the originator of the stream classification system of youth, maturity, and old age. A youthful stream was typified as having a steep, V-shaped valley, a boulder strewn bottom, and a steep gradient. A mature stream was characterized by a balance between erosion and deposition, with a widely meandering course in a wide valley. An old stream, described as not having enough energy to erode its bottom or banks, flowed over a relatively flat gradient, and was primarily depositional. These classifications were extremely easy to apply over large river systems from headwater to mouth, but they had several drawbacks. Discontinuities in the system could not be explained easily; rivers reverted from maturity back to youth with astounding regularity throughout their lengths. A popular misconception, possibly stemming from this concept, is that rivers have a lower velocity at their mouths than at their sources. In truth, the overall velocity or travel rate actually increases or remains nearly constant throughout the length of the river. Perhaps the most troublesome part of this concept was its inability to explain changes in stream characteristics after some non-geologically induced change occurred in the drainage. The geologic time-frame of the Davis concept gave the impression that rivers were static, non-changing entities.

There followed a more detailed consideration of the concept of equilibrium, or grade, as developed by Mackin. A graded stream was described as one in which the slope is delicately adjusted to provide, with adequate discharge, just enough velocity to remove the sediment load supplied by the drainage basin. The graded stream is a stream in equilibrium with its basin under a given hydrologic regime; any change in the basin or the hydrologic regime causes a displacement of the equilibrium which tends to absorb the effect of the change (Leopold, 1962). The single most important result of this concept is the recognition that rivers can change, almost instantly, several factors of their hydraulic geometry (i.e. width, depth, velocity, bed roughness, etc.) to accomodate the displacement. This is a concept which appears to be incompletely understood by many stream ecologists. Many of the reviewed methods note changes in velocity or depth, but do not account for more subtle changes, such as the width to depth ratio, or the load capacity.

Following the concept of a graded stream, it is noteworthy to examine another stream concept, developed by Wolman and Miller (1960). They suggest that most of the geological work done by rivers occurs during events of moderate frequency. The frequent events do not have enough energy to do substantial geologic work, but catastrophic events do not occur often enough to have significant impact. Therefore, a great deal of the geologic work done by a river occurs during the flood stage or during other short duration events each year. The equilibrium of the river is such that even after considerable amounts of scour and rearranging of bottom materials during a flood, the bottom is normally quite similar to what it was prior to the flood (Leopold, 1962). This is extremely important in terms of stream ecology. A certain type of bottom material reflects certain characteristics of flow, and a good many aquatic organisms are associated with these particular conditions. Even a small change in the hydrologic regime can result in a displacement of equilibrium, resulting in a change in one or all of the characteristics of the habitat.

Current ideas are that rivers tend toward a condition of steady-state balance, or dynamic equilibrium. Exact equilibrium is rarely attained, however, and generally the river and its landscape tend toward a mean form, defined only by statistical means and extremes. This dynamic equilibrium condition is demonstrated by the tendency of the river to maximize the efficiency of energy received and utilized, balanced against its tendency to make the efficiency of use constant through time. The tendency toward uniformity in energy use for rivers in equilibrium predicts a maximization of potential biological niches along the length of the river (Curry, 1972).

Under the definitions of maximization of efficiency and minimization of variance, there exists an equilibrium between the inflow of sediment from the drainage and the outflow of sediment at the mouth. This balance is determined by the ratio of sediment and water derived from the drainage basin; a function of runoff, vegetation, and lithology. A permanent change in discharge, such as that resulting from persistent and long-term diversion of water from the system, can be considered to be a change in the hydrologic regime. Under the concepts outlined above, several predictable and fairly well documented changes in the stream habitat can occur (Leopold, Wolman, and Miller, 1964).

Qualitative Effects of Reduced Discharge

Discharge is defined as the volume-rate of flow in a river. The unit of discharge is usually the cubic foot per second (in the U.S.), which can be converted to gallons per minute, acre feet per year, or any other volume-rate unit. The mathematical expression for discharge, used in stream-gaging techniques, is:

$$Q = W \times D \times V$$

Where Q = discharge in cubic feet per second
W = width in feet
D = depth in feet
V = velocity in feet per second

Conceptually, this mathematical expression is important in regard to the frequent controversies between hydrologists and aquatic biologists. A stream may have considerable water in it, but has no discharge if the water is not moving.

The three discharge variables do not change linearly with the discharge. The variables, depth, width, and velocity, are exponential functions of discharge: (Leopold, Wolman, and Miller, 1964)

$$W = aQ^{l}$$
$$D = bQ^{m}$$
$$V = cQ^{n}$$

Where a, b, and c are the y-intercepts and l, m, and n are the slopes of the logarithmic plots of the respective variables against discharge.

Of these variables, velocity changes the most dramatically with discharge in most streams (Curtis, 1959; Fraser, 1971; Hooper, 1972). Most of the biota living in streams are highly current-oriented, making velocity a most important environmental factor. Many species have well defined preferences for velocity ranges, and therefore the velocity is a key factor in species composition. Current velocity is also a major influence on other abiotic factors, such as reaeration rate, sediment capacity, bed scour, and temperature, which in turn may become regulating or limiting factors in the lotic environment (Velz, 1970; Alonso, McHenry, and Hong, 1973).

Fraser (1971) rates depth as perhaps the next most important physical factor in relation to discharge. Depth may change rapidly from one point to another due to channel configuration. A lowered discharge in the stream will affect some reaches more than others. Riffles, for example, are more highly impacted by lowered discharges than are pools (Kraft, 1972). Most stream organisms, at some time in their life cycles, show some definite preference for a given range of depths. Depth may also influence abiotic factors such as the mix-interval for dissolved oxygen, temperature, and the vertical infiltration rate through the stream bottom (Velz, 1970; Coffin, 1968).

Channel width can be important as a spatial requirement. Channel width is also important in terms of primary production, since more plants may be exposed to sunlight in wider reachs. Up to bankfull stage the rate of horizontal and vertical seepage to ground water is largely controlled by stream width, which in turn affects flood plain vegetation.

Sediment transport is also an exponential function of the discharge (Morisawa, 1968). Sediment bearing tributaries may introduce large amounts of sediment which the dewatered stream lacks the capacity to transport (Kraft, 1972). Sediment may cover the original substrate, change the species composition of food organisms, or obstruct the oxygenation of incubating eggs.

Spring discharge affects fish migrations by providing the stimuli for the initiation of spawning, and by providing access to spawning grounds (Hayes, 1953; Davidson, et. al., 1943). Inadequate depth over riffles essentially blocks migration beyond those riffles. Species such as the northern pike, which migrate into flooded shallows, require a high enough spring discharge to cover the spawning grounds (Franklin and Smith, 1963).

Discharge plays an important role in the biogeochemical environment of floodplains, and the organisms that live there. Of utmost importance is the relationship between discharge and vegetation, both aquatic and riparian. In some cases, the absence of high spring runoff will encourage the colonization of the floodplain by riparian vegetation. This vegetation can be both beneficial and detrimental to the stream ecosystem. It will stabilize the banks and reduce bank erosion, shade and cool the water, provide overhead cover for fish, and provide food for detritus-feeding aquatic insects. However, young colonizing vegetation consumes a very large quantity of water. Therefore, it is conceivable that at least one effect of lowered discharge could be its further lowering through the transpiration of an increased riparian vegetation cover. Fraser (1971) observes that the encroachment of willows and other vegetation on king salmon spawning grounds in several California rivers has rendered the spawning areas unusable by salmon even though the stream flow at the time of spawning was entirely satisfactory. Stabilized low flows, or the absence of freshets, can also result in the proliferation of aquatic plants, or hydrophytes. Normal high flows uproot this vegetation and carry it downstream. As rooted vegetation becomes established, it promotes the capture of silt. Thus, the substratum can be altered, promoting further colonization by hydrophytes. Carried to its natural extreme, the channel can in some cases be completely obstructed and entire animal populations altered (Hynes, 1970).

Lowered discharges may also change the species composition, and especially the zonation, of riparian vegetation on the floodplain. The zonation of stream-side vegetation is determined by the period of inundation. Certain species, such as willows, can withstand longer periods of inundation than can others. Absence of inundating flow may result in less tolerant species crowding up to the stream bank (Hosner, 1958). Additionally, Meinzer (1927) reports that each species of phreatophyte has its own limits of survival in terms of depth to ground water. The depth to ground water by the end of the growing season is nearly always determined by the amount of recharge of the aquifer during spring runoff. The survival limits of each species of vegetation are so well defined that it is possible to estimate the maximum depth to ground water by the type of vegetation associations on a given site. For example, cattails and cottonwood trees both indicate a good perennial source of water. In the case of cattails, ground water is seldom deeper than a meter or so. Cottonwoods indicate greater seasonal depths to ground water, usually on the order of 3 to 6 meters. If reduced discharges result in the slow lowering of the water table, the zonation may become compressed; or if the drop in water table levels is rapid, some or all of the vegetation may die or be replaced by a more competitive species.

In addition, some species of plants, such as cottonwood trees, propagate by seed during high spring runoff. It is possible that reproduction may be seriously curtailed by elimination of high spring runoff.

The amount of water in a river is certainly important in terms of water quality. The sheer mass of water is important in the temperature of a body of water. Smaller bodies of water get warmer because there is less water to heat, especially if they are wide and shallow. The volume of water is important in the dilution of wastes, and plays an important role in the assimilation capacity of the stream.

In summary, altered discharges can bring about changes in food production, stimulus and success of migration, spawning, egg survival, space and cover, species composition, water quality and floodplain or terrace vegetation.

STREAMFLOW AND THE STREAM COMMUNITY

Stream Energetics

Hooper (1973) states that the relationships between water flow and the production of food in streams are poorly understood. However, because aquatic systems are often readily quantifiable, much of the research on ecological energetics has been done using an aquatic habitat. Hence, much of what is known about energetics is a result of work done on aquatic systems. Energetics refers to the flow of energy through a system, as opposed to the cycling of nutrients within the system. Essentially, the ultimate carrying capacity for a desirable food or game fish in a stream is determined by the ability of the stream to supply food to those fish. This is determined by the amount of vegetation which is produced in the stream, or which falls in from nearby streambank vegetation.

Possibly the most famous study on ecosystem energetics was Odum's (1957) investigation of the flow of energy through a spring-fed stream at Silver Springs, Florida. Odum calculated the amount of incoming solar energy, and then determined the amount of energy absorbed by each successive trophic level (i.e. plants, herbivores, primary carnivores, and so on). He found a progressive dimunition of energy (expressed as $kcal/m^2/yr$) at each successive level in the food chain. A generalized concept arising from this study is that the energy content of each trophic level is only about 10% of that in the preceeding one. This loss of energy results from the "wasting" of energy in the normal living processes of each organism, through activity, assimilation, excrement, reproduction, etc. The Silver Springs study simply confirmed the first law of thermodynamics. There is no way to come out "ahead" in energetics. Therefore, a stream which is very low in primary productivity will be limited in the number and productivity of trophic levels which can be represented by that stream. This limitation further limits the kinds of fish which may be present, their numbers, and even their sizes.

Primary Production and Streamflow

Hooper (1973) notes several authors who argue that current velocity is of utmost importance in the maintenance of algal communities. The function of the current is in the renewal of needed nutrients and gases at the cell surfaces, and in the removal of impoverished and waste bearing water from the cell surfaces. Prescott (1968) states that while currents are of little importance in the selection and distribution of algae species in lakes, they are highly important in streams. Laboratory experiments have shown repeatedly, that algae absorb nutrients in greater amounts and, hence, grow more rapidly in moving rather than in still water. Whitford and Schumacher (1964) determined that the algal uptake of phosphorus was about 5.1 times greater in running water than in still water, but that the velocity had to be at least 15 cm/sec (0.49 fps) to have any affect on production rates.

The depth of water influences the attenuation of light as it penetrates the water. Sixty percent of the light which is not reflected is lost in the first two to five meters by scattering and absorption. The longer wavelengths of light which are required for algal photosynthesis are the first to be absorbed (Prescott, 1968). However, rivers in the Northern Great Plains are characteristically shallow, and water depth is not as important in these streams as it is in lakes.

A greater factor in the attenuation of light in streams is stream turbidity. Because some algae are favored under conditions of reduced light, the algae species composition might be changed by high turbidities. Vertical distribution is determined by the capacity of different genera with different pigments and metabolic mechanisms to make use of the light that does penetrate the water (Prescott, 1968). Mills, Starrett, and Bellrose (1966) attribute much of the demise of aquatic life in the heavily polluted Illinois River to the loss of all forms of aquatic vegetation due to high turbidity and sedimentation.

Other factors which affect primary productivity and are related to streamflow, are water temperature and water chemistry. While temperature is not as important as light, extremes in temperature can exert selective pressures on the species and determine species distribution. There are, of course, species of algae which grow in the Arctic, and others which flourish in geyser basins. However, most species of algae show an optimum temperature for photosynthesis and reproduction which lies in the range of 10°to 25° C. (Prescott, 1968). It is possible that temperature range and rate of temperature change operate as the most important of ecological factors limiting species of algae.

Water chemistry has often been noted as the most important ecological factor regulating algal growth. Much of the interest in the relationships between species of freshwater algae and water chemistry is no doubt related to the artificial eutrophication of lakes and reservoirs. Because some species of algae require certain nutrients in greater quantities than other species, the presence or absence of optimum amounts of these substances limits species distribution. Prescott (1968) describes the successional sequence of algae in streams primarily as a matter of temperature and water chemistry. Algal production is very low in rapidly flowing streams near headwaters.

At lower elevations, where currents decrease, and temperatures and nutrients increase, the quantity and diversity of algae also increase. Slowly flowing streams in lower reaches sometimes develop blooms of Euglena, Microcystis, or Aphanizomenon which are indicators of high nutrient content. Unpolluted streams characteristically support such filamentous species as Cladophora, and diatoms such as Nitzchia.

Hynes (1972) and others have noted that the standing crop of algae in some streams appears to be insufficient to maintain the populations of herbivores found there. This observation is partially explained by some stream herbivores using leaves and other debris which have fallen into the stream from nearby banks. This allochthonous material is often a major source of vegetable matter for stream herbivores. It is sometimes of greater importance than algae. Chapman (1966b) estimated that in a small stream supporting a coho salmon population, 51% of the aquatic portion of the coho diet had an allochthonous source. This diet includes both terrestrial insects which fell into the water, and aquatic insects which fed on leaf detritus. The detritus was of greater importance as a food source for the aquatic insects than was material produced within the stream.

These investigations point out the importance of riparian vegetation to the energy input of a stream. In general, algae is a more important source of food in riffle areas, where it is most productive, and detritus is more important in pools, where leaves and other organic materials may settle to the bottom. These factors influence the distribution of some stream animals.

In summary, the factors most influencing primary production in rivers are water chemistry, light penetration, temperature, and current velocity.

Stream width is an important factor in total primary production through its effects on total photosynthetic surface area. An important energy subsidy in a river system is terrestrial material which falls into the river.

Streamflow and the Benthic Community

The benthic community is here classified as generally the first trophic group above the primary producers. This is an oversimplification since not all of the members of the benthos are strictly herbivores; some are carnivores, detritivores, or omnivorous in their food habits. Regardless of their diets, members of the benthos have one factor in common; they are food organisms for the next trophic level, the fishes. While the benthic community includes crustacea, molluscs, and aquatic insects, this section will deal primarily with the insects. While the crustacea and some molluscs are certainly important food sources for higher trophic levels, the food supply in rivers appears most dependent on good standing crops of insect fauna. Non-insect food sources will be treated where they are important to the food base.

While little research has been conducted to relate invertebrate production and streamflow, a considerable body of knowledge exists concerning the distribution and life histories of many species. Any experienced aquatic biologist knows where to sample to find the largest number and variety of insects in a river. Most of these food organisms demonstrate definite habitat preferences and distributions. The limits of these microhabitats are often narrow and well defined in terms of depth, velocity, substrate, and food supply.

The following summarizes the various factors which are important in the distribution, abundance, and productivity of the benthos. For a more detailed discussion of this subject, the reader is referred to Appendix I.

Water velocity is a critical variable in the distribution and production of aquatic insects. For some species, current velocity appears to be the most important variable in a stream's hydraulic geometry. Sprules (1947) felt that within the constraints set by temperature, the distribution of species was affected most by current velocity and bottom type. Many species require a fairly narrow range of velocities to fulfill physiological requirements such as food supply or oxygen renewal. While many invertebrates are physiologically adapted to life in high velocity water, many others select a particular velocity range through behavioral adaptations (Macan, 1963).

Because of the turbulence around large substrate particles in swiftly flowing water, a wide variety of habitats is available for invertebrates. Reduced current results in a reduction of habitat variety, and thus may result in a decrease in invertebrate production and diversity. In addition, the reduction in velocity will encourage sedimentation of the interstices between substrate particles, which would select against invertebrates with behavioral adaptations for living in the crevises between the rocks.

Table 1 is a comparison of data from five separate studies which relate water velocity to abundance of stream invertebrates. Since different sample sizes were taken, numerical comparison is possible only within individual studies. The different depths in the water column at which velocity measurements were made may account for part of the variation in results. The depth at which velocity measurements are made should be standardized (i.e. as .6 of total depth, or 3 cm from the bottom, etc.)

TABLE 1: Relationship between water velocity in stream riffles and numbers of bottom organisms in five studies.

Current velocity*		Number of organisms				
cm/sec	(ft/sec)	Pearson, et. al (1970) 1/	Surber (1951) 1/	Kennedy (1967) 1/	Arthur (1963) 2/	Needham & Usinger (1956) 3/
0 - 15	(0 - .5)	----	----	----	138	----
18- 31	(.6 - 1.0)	53	99	444	137	----
34- 46	(1.1- 1.5)	90	148	881	532	90
49- 61	(1.6- 2.0)	120	115	484	257	----
64- 77	(2.1- 2.5)	89	152	289	359	71
80- 92	(2.6- 3.0)	105	125	171	352	99
95- 107	(3.1- 3.5)	65	339**	----	392	80
110- 122	(3.6- 4.0)	62	----	----	365	70

*Surber recorded surface velocity, Arthur measured velocity 3 cm from bottom; depth of other velocity measurements not specified.

** Inadequate sample size

1/ Compiled by Giger (1973)
2/ Compiled by Hooper (1973)
3/ Compiled by author from Needham and Usinger (1956)

so that all researchers are measuring the same relative positions. Results from Table 1 indicate that the greatest numbers of aquatic insects are produced in the velocity range of 34 to 46 cm/sec (1.1 to 1.5 ft/sec).

The depth of water over food producing areas is also quite important in terms of productivity and diversity. Needham and Usinger (1956) found the greatest numbers of insects in riffle areas from 8 to 22.5 cm (3 to 9 inches) in depth, with numbers increasing up to 22.5 cm and decreasing at greater depths. Kennedy (1967) found the majority of bottom organisms in 8 to 15 cm of water.

The bottom type, or substrate, appears to be of equal importance to water velocity in the distribution and production of aquatic invertebrates. Large bottom materials provide the greatest amount of surface area, and in conjunction with velocity and turbulence, the greatest variety of microhabitats (Sprules, 1947). Under natural stream conditions, medium sized stones usually provide the most productive habitats. Kennedy (1967) determined that most organisms were found on or under rocks which were between 6 and 18 cm (2.5 to 7 inches) in diameter.

Sprules (1947) determined that rubble substrates in moderately fast water not only produced the greatest amount of insect fauna, but also had the highest diversity. A high diversity is important in the insect fauna because many fish species feed on very small insect species during the early part of their life histories, and select larger species as they grow. The size of the bottom materials is especially important to insect species with behavioral adaptations for life in running water. Percival and Whitehead (1929) investigated the distribution of invertebrates on substrates which differed primarily in the size of particles and the degree of cementation by sediment between the particles. Table 2 is a simplified version of some of their data. Most genera preferred substrate sizes of between 5 and 30 cm, with little sedimentation between substrate particles.

Substrate size has not been standardized by aquatic biologists in the same terms as those used by hydrologists and engineers. Substrates referred to as rubble in many texts correspond to small to very large pebbles according to the Wentworth Grade Scale. Gravel corresponds to the granule on the Wentworth Grade Scale. The classifications of sand and silt encompass very coarse to very fine particles of each size class, and the size class referred to in many reports as mud corresponds to the Wentworth classification of fine to coarse clay. The Wentworth Grade Scale is presented in Table 3 for standardization of sediment particle sizes.

Inasmuch as substrate type is both a product and a local modifier of hydrologic conditions, Thorup (1966) states that substrate type is a better characteristic than stream zonation to use as a basis for a system of biocoenoses, even though variations occur in the faunal composition on certain substrates. However, because of these variations, substrate alone is not sufficient for the construction of a system of biotopes, and depth and velocity must be considered.

Invertebrate distributions are also influenced by the distribution of invertebrate food sources in the stream. Several authors note that the amount of food produced by algae alone is not sufficient to support the total stream biota. This fact emphasizes the importance of allochthonous material

TABLE 2: Relationship between size of bottom materials and degree of cementation, and the abundance of different genera of bottom invertebrates. (X refers to the bottom type with the greatest number of individuals of a particular genus; / refers to the type with the second greatest number of individuals.

Size range (cm) Degree of cementation Vegetation	5-30 low none	5-30 high diatom	.05-.25 high none	2.5-30 high Cladophora	5-30 low Fontinalis	2.5-30 high Potamogeton
Genus						
Ephemeroptera						
Beatis	X	/				
Rhithrogena	X		/			
Ecdyurus	X	/				
Ephemerella				/	X	
Caenis			X		/	
Plecoptera						
Leuctra	X	/				
Chloroperla	X				/	
Amphinemura	X				/	
Trichoptera						
Polycentropus	X					/
Hydropsyche					X	/
Glossosoma		X	/			
Agapetus	/	X				
Rhyacophila	/			X		
Psychomyia		X		/		
Diptera						
Chironomidae					X	/
Simulium	X				/	
Mollusca						
Limnaea		/				X
Ancylus		X		/		
Crustacea						
Gammarus	/				/	X
Total numbers	94.20	89.58	87.30	96.19	94.55	85.80

*Generally classified here as loose moss. Thick growths of moss had the highest numbers and densities, but were represented primarily by Chironomidae and Oligochaeta.

From: Percival, E. and Whitehead, H. 1929. "A quantitative study of the fauna of some types of stream bed. J. Ecol., 17: 282-314.

Table 3: Wentworth's Particle Size Classification

Diameters in mm	Name	Diameter	Name
128 - 64	Small cobble	1/4 - 1/8	Fine sand
64 - 32	Very large pebble	1/8 - 1/16	Very fine sand
32 - 16	Large pebble	1/16 - 1/32	Coarse silt
16 - 8	Medium pebble	1/32 - 1/64	Medium silt
8 - 4	Small pebble	1/64 - 1/128	Fine silt
4 - 2	Granule	1/128 - 1/256	Very fine silt
2 - 1	Very coarse sand	1/256 - 1/512	Coarse clay
1 - ½	Coarse sand	1/512 - 1/1024	Medium clay
		1/1024 - 1/2048	Fine clay

From Krumbein, W.C. and Sloss, L.L., 1955. Stratigraphy and Sedimentation, W.H. Freeman Co., San Francisco. p.71.

in the aquatic food web. The distribution of food materials in streams is such that the food source in riffle areas is primarily algae, while in depositional areas, detritus is the major food source. However, some detritus settles out in riffle areas as well (Egglishaw, 1964). The primary food source in the stream is seasonally variable, as well as variable in its area of production and deposition. During the spring and fall, the food source is largely allochthonous, and primarily autochthonous during summer and winter (Buscemi, 1966).

Flow stability is important in invertebrate production. Sudden fluctuations in water levels operate to disturb invertebrates by one of two mechanisms: dislodgement in the case of increased flow or stranding in the case of decreased flow (Giger, 1973). Constantly fluctuating streamflow consistently results in the reduction of both production and standing crops of bottom fauna. The effects of flow fluctuation may be qualitative, as well as quantitative, depending on the direction of the fluctuation. If the fluctuation is manifest in a sudden surge of water, the fluctuation will select against free-roving invertebrates, such as the Plecoptera or Ephemeroptera, which are vulnerable to being swept off the substrate. If the fluctuation appears as a sudden decrease in discharge, it will select against forms which are relatively immobile, such as many of the Diptera and Trichoptera.

Flow rates are influenced by the formation of anchor ice during winter months. Anchor ice is a slushy form of ice which forms on the bottoms of streams during cold weather. As the ice builds up during the night, it causes water to be backed up into upstream pool areas. When the ice buildup breaks loose during the day, it is accompanied by a large surge of water and slush. This action dislodges considerable numbers of invertebrates and sets them drifting in the current. Anchor ice formation is a natural phenomenon, and its occurance under normal conditions rarely has a major influence on the abundance of stream invertebrates. However, under conditions of reduced winter discharges, the occurance and severity of ice formation could increase. This could eventually lead to overwinter depletion of food producing areas.

Water quality may have profound effects on the structure and productivity of the invertebrate community. Among the factors influencing water quality, reduced streamflow may have the following impacts, separately or in combination with one another:

1) Greater range of water temperatures, both diurnally and seasonally.
2) Decreased waste assimilation capacity, and lowered dissolved oxygen concentrations.
3) Decreased sediment load capacity and competence.
4) Increased concentration of nutrients.

5) Increased concentration of toxic materials.

Temperature is frequently the controlling abiotic factor in interrelated water quality parameters. It controls the rate of biochemical oxidation of wastes, the solubility of oxygen in water, the metabolic rates of stream animals, and influences the relative toxicities of many toxic materials.

Sedimentation is likely to be a serious water quality problem in dewatered rivers of the Northern Great Plains. This region experiences climatic conditions which lead to very high sediment yields per unit area. Most of the damage done by sedimentation occurs when silt enters a stream at times other than periods when the stream has energy enough to remove it in suspension. Thus, storms occurring in tributary drainages might easily result in large amounts of sediment being discharged into a river which lacks the discharge and velocity to keep it in suspension.

Many invertebrate species are involved in a process known as drifting. This refers simply to insects which have released from the substrate to float in the current. Aquatic drift is the most important mechanism by which invertebrates are removed from the area of production and delivered to the area of greatest use. There is ample evidence to demonstrate that reduced discharge ultimately results in reduced drift rate, either through decreased productivity or insufficient current velocity to remove organisms from the substrate. A decrease in drift rates may result in eventual impoverishment of pool areas, selecting against fish species which rely on this food source.

Many species of aquatic invertebrates are potential competitors with one another. In many of these cases exclusion of one species by another does not occur because of the instability of the physical environment, the variety of habitats, or other factors which prevent one species from being continuously favored over others. Any factor which differentially affects one of two populations contending for a common position in the community structure will affect the distribution and abundance of the species. It is thus important to maintain conditions which do not favor one species over others for an extended period of time. Should this happen, a decrease in insect diversity is probable. A high insect diversity is desirable for two reasons:

1) High diversity ensures a broad range of organism sizes. This guarantees a food source for fish requiring small organisms at one stage in their life histories, but which require larger organisms as they grow.

2) Because different invertebrate species emerge at different times of the year, high diversity helps maintain a continuous food supply throughout the year.

Steamflow and the Fish Community

The organization and structure of a warm-water fish community is considerably more complex than that of a salmonid community. In addition to having more species, the warm-water fishery has more trophic levels. Interspecific relationships, such as competition and predation, are of greater significance in these communities. While trout are primarily insectivorous, most of the "important" or desirable species in a warm-water community are piscivorous. Therefore, species which might be ignored as being unimportant in a salmonid stream, must be considered an integral part of the warm-water system. Table 4 is a list of fish species known to inhabit the warm-water portions of rivers in the Northern Great Plains of Montana.

In their excellent reports of problems related to minimum flow recommendations for salmonid streams, Giger (1973) and Hooper (1973) studied each phase of the salmonid life cycle to determine the critical variables. The format of this section will be similar to those studies, with emphasis on warm-water species. Although trout are known to inhabit the rivers of the Northern Great Plains, their flow requirements are generally well defined. For a more detailed analysis of flow requirements for trout, the reader is referred to the aforementioned studies.

Steamflow requirements for warm-water species have seldom been measured. As a result, many of these requirements must be inferred from successional patterns and local distributions of species. A certain danger exists in inferring flow requirements, not only because they are not directly measured, but also because data have been taken from river systems representing a wide variety of geographical regions. However, data as they appear in

Family	Common name	Scientific name	Drainage*		
			M	Y	L
Acipenseridae	Shovelnose sturgeon	*Scaphirhynchus platorhynchus*	X	X	
	Pallid sturgeon	*Scaphirhynchus albus*	X	X	
Polyodontidae	Paddlefish	*Polyodon spathula*	X	X	
Lepisosteidae	Shortnose gar	*Lepisosteus platostomus*	X		
Hiodontidae	Goldeye	*Hiodon alosoides*	X	X	X
Salmonidae	Rainbow trout	*Salmo gairdneri*	X	X	
	Brown trout	*Salmo trutta*	X	X	
	Brook trout	*Salvelinus fontinalis*	X	X	X
Esocidae	Northern pike	*Esox lucius*	X	X	
Cyprinidae	Carp	*Cyprinus carpio*	X	X	X
	Goldfish	*Carassius auratus*	X	X	
	Golden shiner	*Notemigonus crysoleucas*	X	X	X
	Pearl dace	*Semotilus margarita*	X	X	
	Creek chub	*Semotilus atromaculatus*		X	X
	Lake chub	*Couesius plumbeus*	X	X	X
	Flathead chub	*Hybopsis gracilis*	X	X	X
	Sturgeon chub	*Hybopsis gelida*		X	
	Emerald shiner	*Notropis atherinoides*	X	X	
	Sand shiner	*Notropis stramineus*		X	
	Brassy minnow	*Hybognathus hankinsoni*	X	X	X
	Plains minnow	*Hybognathus placitus*	X	X	X
	Silvery minnow	*Hybognathus nuchalis*	X	X	X
	Fathead minnow	*Pimephales promelas*	X	X	X
	Longnose dace	*Rhinichthys cataractae*	X	X	X

TABLE 4: Fishes of the plains region of Montana. From: Brown, C.J.D. 1971. Fishes of Montana. Big Sky Books, Montana State University, Bozeman, Montana. 207 pp.

* M- Missouri; Y- Yellowstone; L- Little Missouri

Family	Common name	Scientific name	Drainage*		
			M	Y	L
Catostomidae	River carpsucker	*Carpiodes carpio*	X	X	X
	Blue sucker	*Cycleptus elongatus*	X	X	
	Smallmouth buffalo	*Ictiobus bubalus*	X	X	
	Bigmouth buffalo	*Ictiobus cyprinellus*	X		
	Shorthead redhorse	*Moxostoma macrolepidotum*	X	X	X
	Longnose sucker	*Catostomus catostomus*	X	X	
	White sucker	*Catostomus commersoni*	X	X	X
Ictaluridae	Black bullhead	*Ictalurus melas*	X	X	X
	Yellow bullhead	*Ictalurus natalis*		X	
	Channel catfish	*Ictalurus punctatus*	X	X	X
	Stonecat	*Notorus flavus*	X	X	
Gadidae	Burbot	*Lota lota*	X	X	
Centrarchidae	Rock bass	*Ambloplites rupestris*		X	
	Green sunfish	*Lepomis cyanellus*	X	X	X
	Pumpkinseed	*Lepomis gibbosus*	X	X	
	Bluegill	*Lepomis macrochirus*	X	X	
	Smallmouth bass	*Micropterus dolomieui*		X**	
	Largemouth bass	*Micropterus salmoides*	X	X	
	White crappie	*Pomoxis annularis*	X	X	
	Black crappie	*Pomoxis nigromaculatus*	X	X	
Percidae	Yellow perch	*Perca flavescens*	X	X	
	Sauger	*Stizostedion canadense*	X	X	
	Walleye	*Stizostedion vitreum*	X	X	X
	Iowa darter	*Etheostoma exile*	X	X	X
Sciaenidae	Freshwater drum	*Aplodinotus grunniens*	X	X	

TABLE 4 : Fishes of the plains region of Montana. From: Brown, C.J.D. 1971. Fishes of Montana. Big Sky Books, Montana State University, Bozeman, Montana. 207 pp.

* M- Missouri; Y-Yellowstone; L- Little Missouri

** from Allen Elser, Montana Fish and Game Department, Miles City, Montana. Personal communication, February, 1974.

this section, represent flow-related distributions which are common to different geographical areas.

Stream succession

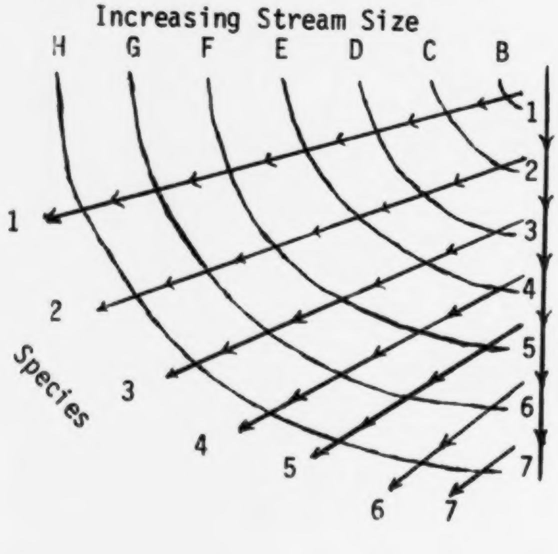
Normally, ecological succession implies the modification of the microenvironment by one species to the point that another species can successfully invade the area and eventually replace the former species. This definition was initially developed by plant ecologists and does not always apply to stream succession. Most fish, for example, have no control over the modification of the stream environment. In some streams, more species are added as the stream becomes larger, but few or none are replaced. In other streams, replacement is a common feature.

Successional patterns have been studied by a number of researchers, each relating fish distribution with some physiographic parameter of the river. Shelford (1911) associated successional patterns with the Davisian concept of stream age. Distribution was related to stream gradient by Burton and Odum (1945), and Trautman(1942). Kuehne (1962), and Larimore and Smith (1963) associated species distribution with stream size. Sheldon (1968) correlated distributional patterns with mean depths of pools.

Successional patterns refer to sections of streams where certain species are found. Local distributions refer to areas within those sections where the species are found the most often. Both the successional distributions and the local distributions will be used to attempt to determine why certain species are found in one place, but not in another.

Shelford's (1911) classic analysis of fish distributions and physiographic conditions gives some insight into the causes of these distributions. Shelford notes that fishes have definite habitat preferences which cause them to be arranged in streams which have a graded series of conditions from source to mouth. Beginning at the sources of the streams in a developmental series, the same species are represented in essentially the same order in all the streams, provided the same series of conditions is present. The only species present in the "youngest" stream are the same as the species nearest the sources of the larger ("older") streams. Fish entering a stream will take a position in the stream which is suited to their ecological constitution without regard to the time and mode of origin of these conditions. Figure 1 demonstrates this distributional concept.

Figure 1: Diagramatic expression of the distributional pattern of stream fishes in streams of differing sizes. From: Shelford, V.E. 1911. Ecological succession. I. Stream fishes and the method of physiographic analysis. Biol. Bull. 21: 9-34.



In Figure 1, the conditions found in stream B are favorable only for one species, yet in H, this species is found only in the headwaters. The direction of reading in succession is indicated by the vertical line with the arrow heads pointed downward. The oblique lines pass through points in the stream profile which have the same physiographic conditions, and which are occupied by similar fish communities.

Krumholtz, Charles, and Minckley (1962), Minckley (1963), Burton and Odum (1945), and Trautman (1942) indicate from their studies that, for the most part, ecological succession in rivers involves replacement of one species or group of species by others as collections were made down the rivers. However, some species were noted to occur the full length of the rivers.

Huet (1959), Sheldon (1968), and Kuehne (1962) all indicate that the succession in streams they studied tended to be additive, with new groups joining the fish community as the streams became larger. Burton and Odum (1945) determined that for some species, succession was an additive process, and for others it was a replacement phenomenon. The size of the stream under consideration may have some influence on species replacement. Certainly, the degree of species specialization and tolerance plays some role in the degree of species distribution. In fact, this may be the most important factor, since fish species with wide environmental tolerances and generalized requirements will likely enjoy a decided competitive advantage if a stream is partially dewatered.

Habitat preferences

This section discusses the distributions of numerous species of warm and cold water fishes. For a more detailed discussion of habitat preferences the reader is referred to Appendix II. Some of the microhabitat preferences have been measured directly, such as those for trout, rock bass, smallmouth bass, and some of the minnows. Most have been inferred from fish distributions in rivers from widely differing geographical and hydrological regions. It is interesting to note the similarity of findings, in view of both geographical and seasonal differences. Of particular interest to this report, is not so much where fish are found, but where they are not. Elser (1972) states that the more water in a stream, up to flood stage, the better the fishery potential. It has been shown that some species are not added to the ranks of the stream fishes until pool depths reach a certain point, but then remain regardless of increasing pool depth. Others remain in an area so long as a certain range of velocities is maintained, with depth not a significant factor.

In order to be certain of what the tolerance limits are for the various species found in the Northern Great Plains, those limits should be measured directly, rather than being largely inferred. However, certain trends are apparent, and distributional patterns do exist, which indicate the approximate position of the lower levels of tolerance for a variety of hydrological parameters in most of the species dealt with in this study.

Tables 5 and 6 summarize the habitat preferences and approximate dimensions of the hydrologic variables which may be considered the minimum tolerance levels of the species given in this section. Table 5 gives values for depths and depth ranges preferred by various species. Table 6 gives approximate values for the preferred velocity ranges. These values are largely inferred. If direct velocity measurements are not made in the field, the approximate range of velocity is determined by the size of bed materials in the species' usual habitat. The velocities reported are fall velocities for the grade of bottom material as given by Morisawa (1968). Since bottom material grade is a function of tractive force, substrate size is also determined by water depth and slope. Therefore, these velocity ranges are approximate. However, inferred velocities agree well with average measured velocities over the various microhabitats, such as brook trout habitats.

These figures point out those species which have rather restrictive habitat preferences. It should be recalled, that when a stream is dewatered, velocity decreases at a much faster rate than any other flow parameter. In terms of dewatering, it is the lower limit of tolerance for any given parameter which is important. Different species will be affected by reductions in different parameters, and some to larger extents than others.

Species which would be most seriously limited by inadequate depth would include: the entire family of Centrarchidae, northern pike, wall-

TABLE 5: Distribution of stream fishes according to depth of water.

Depth in meters Depth in feet ( )	.15 (.5)	.31 (1)	.61 (2)	.91 (3)	1.2 (4)	1.5 (5)	1.8 (6)	2.1 (7)	2.5 (8)
Species									
Stonecat	X	X							
Longnose dace	X	X							
Sand shiner	X	X							
Burbot (est).	X	X	X						
Creek chub	X	X	X						
Pearl dace	X	X	X						
Shorthead redhorse	X	X	X						
Emerald shiner	X	X	X	X					
Fathead minnow	X	X	X	X	X	X			
Flathead minnow	X	X	X	X	X	X	X	X	X
Longnose sucker	X	X	X	X	X	X	X	X	X
White sucker	X	X	X	X	X	X	X	X	X
Black bullhead		X	X	X	X	X	X	X	X
Yellow bullhead		X	X	X	X	X	X	X	X
Channel catfish		X	X	X	X	X			
Rainbow trout		X	X	X	X				
Brown trout		X	X	X	X				
Smallmouth bass		X	X	X	X				
Rock bass			X	X	X				
Northern pike			X	X	X	X	X	X	X
Plains minnow			X	X	X	X			
Silvery minnow			X	X	X	X			
Golden shiner			X	X	X	X	X	X	X
Brassy minnow				X	X	X			
Largemouth bass				X	X	X	X	X	X
Bluegill				X	X	X	X	X	X
Green sunfish				X	X	X	X	X	X
Pumpkinseed				X	X	X	X	X	X
White crappie				X	X	X	X	X	X
Black crappie				X	X	X	X	X	X
Carp				X	X	X	X	X	X
River carpsucker				X	X	X	X	X	X
Smallmouth buffalo				X	X	X	X	X	X
Yellow perch (est.)						X	X	X	X
Bigmouth buffalo							X	X	X
Walleye								X	X
Sauger								X	X

TABLE 6: Distribution of stream fishes according to stream velocity.

Bottom material	rubble	gravel	sand	silt	mud
Size range (mm)	30	5-30	.5-5	.05-.5	.05
Fall velocity (cm/sec)	150	40-150	5-40	.5-5	.5
(ft/sec)	5	1.3-5	.6-1.3	.06-.6	0-.06
Species					
Stonecat	X*	X			
Flathead chub	X	X	X	X	X
Burbot	X	X*			
Longnose dace	X	X			
Shovelnose sturgeon		X*	X		
Sturgeon chub		X			
Shorthead redhorse		X	X		
Blue sucker		X	X		
Smallmouth bass		X	X*		
Rock bass		X	X*		
Rainbow trout		X	X*		
Channel catfish		X	X*	X	X
Longnose sucker		X	X	X	X
White sucker		X	X	X	X
Brook trout			X		
Brown trout			X		
Creek chub			X		
Pearl dace			X		
Emerald shiner			X		
Sand shiner			X		
Plains minnow			X	X	
Brassy minnow			X	X	
Silvery minnow			X	X	
Northern pike			X	X	X*
Walleye			X	X	X*
Black bullhead				X	X*
Yellow bullhead				X	X*
Golden shiner				X	X*
Smallmouth buffalo				X	X*
Yellow perch				X	X*
Sauger				X	X*
Carp				X	X*
River carpsucker					X
Largemouth bass					X
Bluegill					X
White crappie					X
Black crappie					X

*Indicates preferred range if species found in more than one habitat.

eye, sauger, yellow perch, golden shiner, plains, brassy, and silvery minnows, carp, carpsucker, smallmouth and bigmouth buffalo.

Depth of water over normally shallow areas is important to a small number of species including: sand shiner, burbot, and stonecat. Many of the other species frequenting shallow riffle areas can survive extremely shallow water, and would likely not be affected by dewatering unless the entire riffle area became exposed.

Reduced current velocity is not an important factor for some species. In fact, a number of species would prefer reduced velocities provided that pools remained deep enough. Several quite important species are very seriously affected by reduced current velocities. Among these are the salmonids, burbot, sturgeons, stonecat, longnose dace, sturgeon chub, blue sucker, smallmouth bass, rock bass, sand shiner, and possibly the creek chub and channel catfish.

Some species are intimately tied to in-stream or overhead cover, while others actively shun cover of any kind. Among those species which require some form of cover are the entire families of the centrarchids and salmonids. Other species actively using cover would include the northern pike, sauger, walleye, fathead minnow, golden shiner, silvery and plains minnows, and carp.

Research has been conducted, primarily with aquatic invertebrates, to establish "indicator species" for monitoring water pollution. The indicator species are usually organisms which are extremely intolerant and disappear rapidly on contact with the pollution. It may be possible to establish "indicator" fish species, which have restrictive enough habitat requirements that they will leave an area when conditions become too unfavorable. Since velocity is the hydrologic parameter which changes the most rapidly with reduced discharge, those species with definite lower limits of preferred velocity, such as the salmonids, sturgeons, or stonecat, could be used to indicate unfavorably low velocities. These in turn, could be used to indicate favorable conditions for potentially dominating species such as carp, buffalo, or carpsucker.

Food Habits

As with habitat preferences, the food habits of a warm-water fishery are varied and complex. However, they have been studied in greater detail than have habitat preferences. A general ecological principle states that the more complex a community is, the more specialized its members become. This principle applies to food habits as well as habitat differentiation. In pools, hierarchies often develop through competition for food (Chapman, 1966). However, competition between species can be reduced by several mechanisms of ecological isolation. Species may simply eat different things, so that there is no competition. In other cases, competition may be reduced by taking prey by different means. For example, trout feed largely on drifting insects, while the white sucker feeds on the same insects, but largely on the pool bottom. Several species show size preferences, and will not eat prey smaller than the optimum size unless it is the only size available. Concentrating feeding activities during different times of day or different seasons reduces direct competition. Therefore, how, where, and at what time a species feeds is often as important as what it eats. This section reviews food sources and describes the species which utilize those food sources as a primary energy source.

The food eaten by a species is often a reflection of its preferred habitat. As it is with aquatic invertebrates, this holds most true for the herbivorous fishes. Where the food is taken is often a reflection of the physiology of the fish species.

Bottom feeders frequently have downturned mouths with which they can forage the stream bottom. It is sometimes difficult to determine if a bottom feeder is actively searching for aquatic invertebrates on the bottom, or simply taking them in accidentally while feeding on detritus on the stream bottom. Generally classified as bottom detritus feeders are the carp, northern redbelly dace, shovelnose sturgeon, silvery minnow, brassy minnow, plains minnow, fathead minnow, river carpsucker, bigmouth and smallmouth buffalo, and possibly the longnose and white suckers.

Bottom feeders which seem to actively seek out bottom invertebrates might include: the shorthead redhorse, pallid sturgeon, creek chub, longnose dace, blue sucker, burbot, longnose and white suckers, and stonecat.

Several species are known to take drifting or otherwise open water food items. The salmonids are famous for their dependence on drifting invertebrates. Other species frequently utilizing drifting insects or zooplankton include: golden shiners, young northern pike, creek chubs, flathead chubs, emerald shiners, sand shiners, rock bass, young white crappies, young and adult black crappies, young yellow perch, sauger, and walleye, and bluegills. The young of largemouth and smallmouth bass are also known to take drifting invertebrates.

The adult of several species are almost entirely piscivorous. These include: northern pike, burbot, rock bass, smallmouth bass, largemouth bass, white and black crappies, yellow perch, sauger, and walleye.

Three species, black and yellow bullhead, and channel catfish are omnivorous and opportunistic. These species will feed on nearly anything of appropriate size.

The fact that most of the important warm-water game or food fishes are piscivores emphasizes the importance of the forage species. Beyerle and Williams (1968) found that northern pike select minnows and small suckers over centrarchids or bullheads. These results led the authors to believe that the pike, possibly the most voracious feeder of all the game fish, would not be effective in controlling pan fish populations. Large populations of appropriate sized, soft-rayed food fish species favor good growth of pike. Johnson (1969) found that pike would take bluegills readily, but that they selected yellow perch more frequently than bluegills in proportion to their abundances. Johnson concluded that the pike was not likely to control bluegill populations if perch or other cylindrical fish are present.

Nearly all piscivorous species begin their lives feeding on small food, such as small crustacea, Chironomidae, and small Ephemeroptera. They shortly graduate to larger food sources such as the larger Ephemeroptera or other aquatic insects, and most begin feeding on fish soon after, although aquatic or terrestrial insects may be seasonally important.

Of the forage species, Brown (1971) delimits those which he considers to be important to different warm-water game fish in Montana: the golden shiner, creek chub, flathead chub, lake chub, emerald shiner, sand shiner, brassy minnow, plains minnow, silvery minnow, longnose dace, and young of the longnose and white suckers. Of these, the emerald shiner is thought to be a very important forage species for pike, perch, bass and crappies. Lake chubs serve as important forage for trout, pike and walleye, and the flathead and creek chubs are important for sauger, pike and channel catfish. Little mention is made by Brown as to the importance of the yellow perch as an intermediate fish in the food chain. Many studies of the food habits of a variety of large game fish, especially the northern pike, walleye and sauger, show that these fishes feed extensively on yellow perch when it is available. Its slow swimming speed, palatability, and "dawdling" habits make the yellow perch an ideal forage species (Herman, et. al., 1959). It is interesting to note, that while these highly predatory fish will likely eat anything of the proper size and shape, only a few species are considered important as forage fish. This is a function of the availability of the species. The fathead minnow, for example, is not an important forage fish mainly because it resides in areas not inhabited by game fish. The carp or river carpsucker are not important forage species for two primary reasons, their body shape and their fast growth rate. Deep bodied species are hard to swallow when small, and impossible when large (Sigler, 1958).

The importance of the sucker species as forage is largely in question. Undoubtedly, young suckers are utilized as forage by a wide variety of predators, and adults are known to be taken on occasion by northern pike. However, Chen (1969) found that the burbot would not feed on white suckers, even though they inhabited the same areas and the sucker was easily available. Olsen (1963) determined that suckers can be used as forage only for a short time because they grow rapidly and can avoid predation. However, their fast growth rate may make suckers extremely important to larger predators, such as northern pike, walleye and sauger.

The effects of reduced streamflow may have impacts on both the quantity of food items available, and on the feeding behavior, especially of the sight feeders. Chapman (1966) notes that salmonids probably cannot survive on the benthos available within their territories, and must rely heavily on incoming organic drift. This relationship presumably holds for other species as well. Moving organisms stimulate feeding, especially in sight feeders. It is probable that during times of increased invertebrate drift, forage fishes show an increase in their activity. This would tend to make them more available for predation by the piscivores. This seems especially plausible when the hunting behavior of the important game species is considered. The northern pike, smallmouth, and largemouth basses in particular are "sit and wait" hunters, remaining motionless in or under cover until a forage species passes fairly close to its hiding place and is caught. The probability of predator-prey encounters of this type is increased with increased activity on the part of the prey species. Lowered stream velocities decrease the amount of normal invertebrate drift, which results in a decrease in the rate of replenishment of food in a pool, but which also results in a decrease in the activity, and thus the availability, of food fishes for species which do not necessarily rely directly on the drifting invertebrates as a food source. Thus, the rate of drifting of insects into a pool may affect a northern pike indirectly by its effects on forage species.

Giger (1973) notes that since growth is influenced by the amount of energy expended to obtain food, and more foraging may be required to obtain adequate food at reduced flows, there is a potential for reduced growth at lower current velocities. This concept seems appropriate for salmonids that depend on drift resources to a large extent, but has not been documented.

One can speculate at this point in regard to the importance of invertebrate drift to a warm-water community of fishes. If the relationship to drift is positive in a species, as it is in the salmonids, it is likely that a decrease in the amount or rate of drift will initially favor bottom feeding. If the food supply becomes limited, there may be increased foraging on the part of prey species, and thus, increased predation by the piscivores. However, depletion of available food resources as a result of decreased organic drift seems inevitable. This could result in both quantitative and qualitative changes in the fish fauna. Insectivores would be selected against, which could lead to the eventual displacement of the major predator species as well. Bottom ooze feeders would probably be favored by such a situation, and might become the dominant species in the pool. Thus, it appears that the effects of reduced streamflow on the rate of drift are crucial to the community structure.

Spawning

In order for a fish species to be successfully established in a stream, it must not only be able to find suitable habitat and food, but must also be able to reproduce. Loss of reproduction capability frequently results in the costly process of fish stocking.

Spawning success is determined by a number of factors: fecundity, or the number of offspring produced per reproductive effort; survival of the eggs after fertilization; and survival of the fry after hatching.

Fecundity usually refers to a hereditary trait, and in its strictest definition, refers to the number of eggs laid by the female. In this sense, streamflow effects would be indirect, limiting the size of spawning females. However, in terms of total eggs laid and fertilized, streamflow can be a major influence by limiting passage, not providing the proper stimulus for migrations, or by failure to provide adequate spawning sites. Once the eggs are laid, streamflow effects maintain a dominant role in their survival. Such factors as sedimentation, temperature, and a desiccation of eggs are all directly related to streamflow. Survival of fry is also strongly dominated by streamflow through its effects on adequate cover and availability of food. As has been suggested throughout this report, any factor which differentially affects a species in a community can lead to major qualitative shifts in the community structure.

Spawning conditions are listed by species in Table 7. For a more detailed explanation of spawning requirements the reader is referred to Appendix III. It is possible that reduced discharge will have selective effects on reproduction. Species most likely to be affected by reduced streamflow are those which have some particular streamflow requirement, such as velocity, silt-free substrate, or adequate opportunity for migration. Species which prefer to spawn in shallow, still water will find greater spawning opportunities under conditions of reduced streamflow. Species such as the northern pike, while preferring shallow, still water for spawning, may find the water level during spring runoff too far from the needed vegetation for successful spawning to occur.

Species probably affected by reduced discharge can be classified by the hydrologic condition which will most likely affect its spawning site and egg survival. Species directly influenced by a reduction in current velocity include: trout, sturgeon, paddlefish, creek chub, longnose dace, white sucker, longnose sucker and shorthead redhorse. Species affected by increased sedimentation of the stream bottom would include all of the above

TABLE 7: Spawning requirements and fecundity of selected species of fish of the Northern Great Plains Region. Numbers following species name refers to month(s) of spawning activity.

Species	Cover	Substrate (type)	Depth (meters)	Velocity (cm/sec)	Temperature (^{o}C)	Fecundity eggs/fish (max)
Brook trout(9-10)	X	Gravel	.15	15 - 91	3 - 7	2000
Brown trout(10-12)	X	Gravel	.15	40 - 52	6 - 13	6000
Rainbow trout(4-7)	X	Gravel	.15	43 - 82	7 - 13	6000
Creek chub(3-6)		Gravel	ND	49 - 91	ND	4000
Smallmouth bass(5-6)	X	Sand-rubble	0.9 - 1.8	11	15 - 18	35000
Largemouth bass(5-6)	X	Root-debris	0.3 - 1.8	Still	16 - 18	35000
Bluegill(5-7)	X	Firm sand	0.3 - 1.2	Still	16 - 20	30000
White crappie(5-6)		NA	0.6 - 2.5	Still	15 - 18	15000
Black crappie(5-6)		NA	0.2 - 6.0	Still	15 - 18	25000
Black bullhead(5-7)		Mud-sand	0.6 - 1.2	Still	24 - 27	8000
Yellow bullhead(5-7)		Mud-sand	0.3 - 1.2	Still	24 - 27	6500
Channel catfish(5-7)	X	NA	NA	NA	24 - 27	8000
Shovelnose sturgeon (est)(5-7)		Rubble	0.3 - 0.9	75 - 150	ND	ND
Paddlefish (est)(5-7)		Gravel	Variable	49 - 91	16	250000
Longnose sucker(4-6)		Gravel	0.2 - 0.3	31 - 45	5	100000
White sucker(4-6)		Gravel	0.2 - 0.3	31 - 45	10	100000
Shorthead redhorse(4-5)		Gravel	0.3 - 0.9	31 - 61	ND	27000
Northern pike(3-5)		Marsh grass	ND	Still	9 - 11	100000
Golden shiner(5-8)		Vegetation	ND	Still	ND	ND
Carp(5-7)		Detritus	.15	Still	14 - 17	500000
Sand shiner(6-8)		Sand	ND	ND	24 - 27	800
Fathead minnow(5-8)	X	Variable	.03 - 0.6	Still	16	3000
Longnose dace(5-6)		Gravel	.03 - 0.3	15 - 45	ND	4000
River carpsucker(5-7)		Debris	.15	Still	15 - 17	150000
Smallmouth buffalo(5)		Variable	.15	Still	16 - 18	600000
Yellow perch(4-5)		Variable	1.5 - 3.1	Still	16 - 18	40000
Walleye(4-5)		Gravel	1.2 - 1.5*	0 - 50	9	100000
Sauger(4-5)		Gravel	1.2 - 1.5*	0 - 50	6	100000

*estimated optimum depth based on egg survival
- ND; not determined. - NA not applicable

species, with the addition of the centrarchid family and the perch family. Migratory species, such as paddlefish, white and longnose suckers, and walleye and sauger, would be affected by inadequate water depth over riffle areas during time of migration. Of these, the paddlefish is the deepest bodied, and would require the greatest depth clearance over riffle areas. However, the depth which can be cleared by the paddlefish is not known.

Species least likely to be seriously affected by reduced discharge during spawning would include: carp, golden shiner, river carpsucker, bigmouth, and smallmouth buffalo, black, and yellow bullheads and channel catfish. However, egg survival in the carp, golden shiner and the three catostomid species--as well as in the northern pike--is severely affected by fluctuations in water level. The critical factor for successful reproduction in the catfish family appears to be adequately high water temperatures.

In the section on habitat requirements, the identification and use of "indicator" species was suggested. In the case of spawning requirements, it might also be possible to define indicator species. If the requirements of the indicator species are met, the probability is high that the requirements of other species will also be met.

As mentioned in Appendix III, paddlefish migration did not extend upstream as far as usual during the spring runoff of 1973 (See Appendix III). However, most species including paddlefish, were probably able to spawn that season. Therefore, if the discharge is high enough for the successful migration of the paddlefish, it would probably be high enough for the successful reproduction in species which spawn at the same time.

The exact requirements of the northern pike, in terms of streamflow, are unclear at this point. It would seem that the best spawning opportunity for the pike would occur when the river covered its floodplain, which suggests the need for a normal flooding sequence in the river's hydrologic regime. If this is the case, perhaps the northern pike could also be used as an indicator species. The depth of water over the floodplain during pike spawning is variable. However, Fabricius and Gustafson (1958) state that spawning pike always maintain at least 5 cm (2 in) of water between their bodies and the bottom of the spawning bed. Scott and Crossman (1973) state that northern pike can successfully spawn in water as shallow as 17 to 18 cm (about 7 in).

Before potential indicator species can be used in establishing spawning criteria, several critical pieces of information are required. The clearance requirements of the walleye, sauger, and paddlefish must be determined. Possibly, this can be estimated from body depth as was done with the northern pike. Research should also be conducted to determine the relationships of various stimuli to initiation of spawning, especially in cases where two concurrent stimuli are apparently required. Special consideration must be given to those species which do not spawn at the same time as do the indicator species. For some of these species, such as the brown trout, these criteria are known, but for many others, they are largely unknown.

Continuous monitoring of the populations of generalized spawners, such as carp or smallmouth buffalo, should be included as an integral part of any flow recommendation study. These species, because of their generalized habits, could become dominant, with the eventual elimination of other, more desireable species.

Water quality

In many ways, water quality is as much a part of the physical environment of a fish community as current velocity or depth. Like other physical parameters, there are optimum and minimum conditions under which a species will survive, grow, and reproduce. Also, like other physical parameters, conditions of water quality can exert differential effects on the distribution and abundance of fish species. While there are a great number of topics which could be discussed under the heading of water quality, this section will deal primarily with four aspects: temperature, dissolved oxygen, suspended sediment, and nutrient enrichment.

Temperature:

Many species are limited in their distributions by temperature. That fishes are extremely sensitive to changes in temperature was demonstrated by Bardach and Bjorklund (1957). These researchers found that fish representing four families could often detect changes in water temperature of less than 0.1°C. However, stream fish probably do not react to these small changes in temperature. The aspects of temperature which are of importance are those which govern distributions, by providing temperature conditions high enough for suitable growth, but which are not fatal; or by providing the proper conditions for initiation of spawning, egg development, and fry survival.

Bailey (1955) reports a temperature-induced fish kill in a shallow lake. The water temperature at the time of the kill was 38°C (100.4 F). The temperature in the pond at the time of the mortality should not necessarily be interpreted as being below the maximum lethal threshold for those species surviving. The mortality reported resulted from a very short exposure to a high temperature. Therefore, the true upper lethal limit is probably lower than might be inferred from these data. Several species, including killifish and gambusia topminnows, demonstrated little distress due to the high temperatures. Small sunfishes such as bluegills and pumpkinseed did not appear seriously disturbed. What Bailey describes as "probably the only largemouth bass in the lake" was visibly sluggish, but could still avoid capture. The only centrarchid visibly affected by the high temperature was the rock bass. In contrast to this hardiness, golden shiners, fathead minnows, black bullheads, suckers, and darters were all dead or dying.

Trout are not usually found in stream portions having summer temperatures in excess of 21°C (70° F) for any length of time. A good trout stream should have temperatures in the range of 10° to 15.5° C (50-60° F), with an upper limit of 20° C (68° F) (Hooper, 1973). However, the rainbow and brown trout are known to have higher temperature tolerances than the brook trout (Brown, 1971).

Insufficient data exists for the presentation of other than singular examples of the differential effects of temperature. The upper lethal temperatures have not been determined for many species. Those determined may in fact, show little more than designations of water temperature tolerances as being cold, cool and warm, since many species will desert an area before the lethal temperature is reached. Table 8 shows the relative tolerances of a number of species to a variety of water quality parameters, including temperature.

TABLE 8: Relative tolerances and requirements of selected fish species for various water quality parameters.

Species	Water quality parameter High summer temperature* (tolerance)	Dissolved oxygen** (requirement)	Turbidity (tolerance)
Shovelnose sturgeon	ND	moderate	high
Paddlefish	ND	moderate	high
Rainbow trout	low	high	low
Northern pike	moderate	moderate	moderate
Burbot	low	high	high
Smallmouth bass	moderate	moderate	low
Largemouth bass	moderate	moderate	low
Bluegill	high	moderate	moderate
White crappie	ND	moderate	high
Black crappie	ND	moderate	low
Walleye	ND	moderate	low
Sauger	ND	moderate	high
Shorthead redhorse	ND	moderate	low
White sucker	high	moderate	high
Black bullhead	high	low	high
Channel catfish	high	moderate	high
Stonecat	high	ND	low
Golden shiner	high	moderate	low
Carp	high	low	high
Smallmouth buffalo	high	low	high
River carpsucker	high	low	high

*Low tolerances under 20^{o} C, high tolerances above 28^{o} C

**Low requirements from 3-4 mg/L; moderate from 5-6 mg/L; high above 6 mg/L

Dissolved oxygen:

Stroud (1967) states that the dissolved oxygen levels should not fall below 5 mg/L for a healthy warm-water fish population, and a minimum of 6 mg/L should be set as the criteria for salmonids. However, Doudoroff and Shumway (1967) note that the rates of growth and embryonic development, and the activity of fish can be limited by oxygen supply even when it is near saturation levels. Yet, oxygen levels well below 3 mg/L can be tolerated over long periods by some fish and embryos. Moss and Scott (1961) found that the lowest tolerated dissolved oxygen concentrations were lower if the concentration decreased slowly rather than rapidly. They also determined that the lowest tolerated dissolved oxygen concentrations were lower at low temperatures.

Thompson (1925) determined the relative oxygen tolerances for a number of warm-water species in the Illinois River. Thompson first determined which species were present in various locations, then measured the dissolved oxygen concentrations in those locations. He found that the presence or absence of species was closely related to the dissolved oxygen concentration at the time of collection. Thompson also noted that fish retreat into backwater and mouths of tributaries when dissolved oxygen becomes limiting. Animals which are more sedentary and cannot avoid oxygen depletion, such as snails or some aquatic insects, probably suffer more severely than do the fishes. Data from Thompson is included in the summary of water quality parameters in Table 8.

Suspended sediment:

Sediment has been mentioned several times as producing major ecological impacts in streams. These impacts can be caused from sediment in suspension, or when it is deposited in areas where it does not normally settle out. It has been suggested in this study, that hydrologic conditions should be maintained in such a fashion, that the character of sediment in a given location does not change in short time periods. Thus, areas which are typically rubble-bottomed riffles should not develop into gravel bars. This aspect of sedimentation affects fish indirectly, through its effects on reproduction and food production.

Suspended sediment, while often affecting respiration in insects and fish alike, may be more serious in its selection against sight feeders. In highly turbid waters, fish which must see their prey simply cannot do so. In turbid water, these species are at a disadvantage when competing with such fish as carp, buffalo, and carpsuckers. However, even some bottom feeders are intolerant of turbidity. The shorthead redhorse, for example, is a bottom feeder, but is one of the first species to succumb to continuously turbid water (Eddy and Surber, 1943). Stroud (1967) states that while turbidity will vary from place to place, areas with historically turbid conditions should be clear enough that a Secchi disk is visible at depths of 38 cm (15 in) or greater. Even under these conditions, certain species may be favored over others. The tolerances of a number of species for turbidity are generalized in Table 8.

Nutrient enrichment:

Increased concentrations of nutrients, combined with the effects of a greater proportion of stream width which is unshaded, may result in increased production of algae. In lakes, this phenomenon is particularly troublesome, as it frequently results in oxygen depletion when the algae decomposes. In a river with adequate flow, this problem is generally overridden by natural reaeration within the stream. However, the increased growth of algae can result in lowered visibility in the water, and like suspended sediment, act to select against sight feeding species (Haines, 1973). In addition, when the algae settles to the stream bottom in quiet pools, lowered oxygen concentrations may result. This detritus then becomes an additional food source for bottom ooze feeders.

As has been shown for other physical parameters, the effects of water quality seldom operate to eliminate the entire fish community. However, serious qualitative changes can occur rapidly with changes in water quality. Reduced discharges will tend to result in higher summer temperatures, lower dissolved oxygen concentrations, increased sedimentation of inorganic material, increased concentrations of dissolved salts and nutrients (which may result in increased algal production in pools) and lowered visibility due to suspended organic material. Each of these parameters probably affects each species differently and to various extents. However, while each parameter separately has an effect, the combined action of all parameters acting concurrently places severe limitations on species tolerances. Thus, those species which are likely to be selected against are those which have a low tolerance for any single paramter. Since nearly every species is at least slightly intolerant of one or more parameters, species which have relatively high tolerances for all water quality parameters would be favored. These would include the carp, buffalo, and carpsucker, but might also apply to white suckers, bullheads and catfish.

Biotic factors

There are two ways in which data may be organized and generalized for ecological study. The first is to divide the data according to location and surroundings. The assemblage of species from each geographical or ecological situation is then treated separately, as a local animal unit. The other method is to treat all the data as a mass, without local subdivision, and in such a way as to bring out the association of the different species with each other (Forbes, 1907). Preceeding sections have dealt with the relationships of fish species and their physical environment. This section will deal with interspecific interactions; but to totally divorce these interactions from the effects of the physical environment is unwise due to the effects they have on biotic interactions. The biotic relationships discussed will primarily concern competition and diversity, and differential effects of the physical environment, or biotic interaction on these relationships.

Competition:

Competition is defined as the common demand of two or more individuals or species for a resource which is in short supply. Two or more species with identical patterns of resource utilization should not be able to co-exist in a stable environment. This is the ecological principle of competitive exclusion. The ecologist, confronted with the reality of the co-existance of dozens of species with a similar mode of life, has nevertheless accepted the competitive-exclusion principle with a reverse twist. It has become a truism that no two species occupy the same niche (i.e. their food or habitat are never completely identical); so that competition exists with varying degrees of severity, but seldom to the point of rendering a species extinct (Riley, 1953). Larkin (1956) further states that because of the diversity of habitats and food sources offered by freshwater environments, often subject to sudden change, there is little opportunity for specialization by stream fishes. This is reflected in the versatility of fishes and the resulting complexity of interspecific relationships.

That competition does occur is certain, as measured by its end results. The most easily recognized competition interaction is the "coarse fish problem." Three types of competition generally occur in a fish community: for food, for spawning sites, and for space. While competition may not always involve the extinction of a species in an area, it often does. When competition is not so complete as to eliminate a species, the frequent result is a community composed of stunted populations of both species (Larkin, 1956; Bennett, 1944).

Chapman (1966a) states that the nature of competition changes seasonally. During the summer and fall, competition in salmonids is primarily for food and space. During the winter, most species do not feed heavily, and competition is primarily for suitable space where the rigors of winter conditions can be avoided. During spring, the major form of competition is for spawning sites.

Competition for food is often a general factor affecting the fish community as a whole. Interspecific competition becomes more intense when two species tend to feed on the same type or size of food organism. Bennett (1944) notes that a dominant brood or year class of a predatory species can affect the survival of young of all other species, either through active predation of the young, or through more efficient predation of other food items. This condition can remain until a sudden die-off of the dominant year class so reduces its numbers that other species can be re-established. This type of relationship has been noted often for the bluegill-largemouth bass combination. A large dominant year class of bluegills can depress the number of bass. Eventually, bass may be completely eliminated with the resulting fish population composed primarily of stunted bluegills. Beckman (1941) reports essentially the same phenomenon in a combined population of rock bass and yellow perch. In this situation, the yellow perch outnumbered the rock bass four to one, resulting in the stunting of both populations. Following thinning of the populations, the growth rate of rock bass increased dramatically.

While the abundance of food is very important in determining the growth rate of fishes, Van Oosten (1944) suggests that on the whole, the role of competition for food is overemphasized. The possibility that a lack of space may inhibit growth, independently of any competition for food, should not be overlooked. A close relationship exists between population density and growth rate, even when food is plentiful.

Fabricius (1951) notes that territoriality in fish closely resembles that of birds. The boundaries of a territory are not fixed, but to a large extent are elastic. Usually large fish require a larger amount of space than do small fish. Where there is an abundance of in-stream cover and visual isolation, the size of individual territories is smaller than in areas where there is virtually no cover or isolation. For, example, the area within pools and the number of pools suitable for bass may determine the population density that a stream can support, and would vary only as the habitat changed (Larimore, 1954).

Competition is manifested by two basic mechanisms, exploitation and interference. In the two examples of competition given above, the mechanism is primarily exploitive, and the result of one species being better able to utilize a resource than another under a given set of conditions. In interference, one species actually decreases the ability of another species to utilize its needed resources. The best known example of an interfering competitor is the carp.

During its feeding activity, the carp forages on the stream bottom, uprooting vegetation, and generally maintaining a condition of high turbidity in the water. By keeping the water constantly roiled, the carp interferes with the ability of sight feeding species to detect and capture food. By tearing up rooted vegetation, the carp destroys needed cover for species which are associated with aquatic vegetation. During the spawning season, the behavior of the carp is especially disturbing to fish species which build and guard nests, such as the centrarchids. Like plant species which shape the characteristics of the microenvironment, the carp may be considered an ecological dominant (Larkin, 1956; Cahn, 1929; Bennett, 1944). The carp is not the only species with the capabilities of attaining dominance, however. The buffalo species (Ictiobus spp.) and the carpsucker, have habits enough like those of the carp, that they could also become dominant.

Dominance, and its converse, diversity, are not products simply of environmental conditions or species interactions alone, but contain aspects of both factors. Several mechanisms, most of which are not mutually exclusive, have been proposed to explain the variations found in species diversity (Collier, Cox, Johnson, and Miller, 1973). Of these, four are of particular interest to the discussion of factors which may lead to a dominant species or species complex. These are:

1. The environmental stability hypothesis.
2. The spatial heterogeneity hypothesis.
3. The productivity hypothesis.
4. The predation hypothesis.

The environmental stability hypothesis assumes that relative constancy or predictability of favorable conditions for a given group of organisms, increases species diversity by guaranteeing the availability of critical resources, and ensuring favorable growth and reproduction conditions.

The spatial heterogeneity hypothesis states that a larger amount of spatial variation in environmental conditions provides a greater number and variety of available habitats for specialized species.

The productivity hypothesis states that a higher rate of energy flow per unit area of habitat will allow more species to exist through increased specialization in food resource use. In a highly productive environment, sufficient energy reaches higher trophic levels to support additional species (such as piscivores) which would be unable to gather sufficient food energy in a less productive environment.

The predation hypothesis states simply that the presence of a predator can increase the diversity of a community by maintaining prey populations at levels below the carrying capacity of the system.

Each of the above hypotheses is reasonable, and examples for which they are true can be found with little difficulty. However, the evidence is often contradictory for demonstrating one or all of the theories. For example, the environmental stability hypothesis is commonly applied to tropical rain forests where optimum environmental conditions exist year round, and species diversity is extremely high. However, a disturbance in such a system can be extremely devastating,requiring many years to regain its original conditions. Therefore, communities may be considered to be in a state of dynamic equilibrium with the prevailing environmental conditions. In a stream community, the prevailing condition is one of constant change. Thus, the equilibrium condition of the stream community is geared to change, which in turn, may maintain a given level of species diversity.

It has been shown that potentially dominating species generally have relatively high fecundities, have broad and generalized habitat and food requirements, and often interfere with the life histories of other species. Thus, in a stable environment, such as a constantly dewatered river, these species would be least affected in any phase of their life histories. Fish such as carp are thought to be able to replace game fish only after the environment has degraded below optimum conditions for the game fish. Carp are especially favored by conditions of warm temperature, still water, siltation, and low dissolved oxygen concentrations. Additionally, carp are relatively free from fatal diseases or effective enemies. All of these factors, combined with the high reproductive potential of the carp, operate to favor the ascendency of carp over other fish (Sigler, 1958). It has also been demonstrated that factors which do not favor the carp are nearly all related to environmental fluctuations. In a constantly changing environment, the carp does not have a competitive advantage, and is not likely to become dominant, provided that the fluctuations remain within tolerable limits for other species.

For freshwater fisheries, a new hypothesis might be proposed to replace the environmental stability hypothesis. For lack of a better phrase, it might be called the disturbance hypothesis. Dr. A.L. Sheldon, a community ecologist at the University of Montana, gives several examples of high species diversity levels being maintained by constant disturbance. These disturbances favor no single species or species group, but maintain conditions under which all species can survive and reproduce on an equal basis. This hypothesis is actually an extension of the spatial heterogeneity principle. Under normal conditions of daily and seasonal fluctuations, a wide variety of habitats is available. A reduction in discharge, with its accompaning hydrological effects, results in a simplification of habitat structure. This results in a reduction in the complexity of community structure, and can eventually lead to a dominant group.

The problem of biotic interactions can be resolved into two basic issues, productivity and balance. Productivity simply refers to the capacity of a stream to produce fish biomass, regardless of what kind. In its simplest form, streamflow management would likely attempt to maintain high productivity by insuring adequate flow over riffle areas for the production of aquatic insects. Balance refers to the far more sensitive issue of fish quality, and the equitability of the distribution of fish biomass among the species. To assert that a balance of game fish to rough fish is impossible would be rash, as this type of balance is common in many fish communities (Ricker and Gottschalk, 1941). However, the scale is shifted heavily in favor of the rough fish under conditions of reduced discharge. Therefore, minimum flow recommendations must minimize this tendency, by maintaining conditions favorable to the game species, as well as ensuring adequate productivity for all species. This means that flow variability is probably as essential as productivity and suitable habitat in preventing the eventual dominance by rough fish.

Summary of streamflow and the stream community

Reduced discharges may affect the stream community in a number of ways. Essentially, the problems related to reduced streamflow may be considered in terms of productivity and balance. Productivity refers to the carrying capacity of the stream, or its capability of producing fish biomass. Balance refers to the qualitative changes in community structure which may occur as a result of changing environmental conditions which favor one species or species group over others.

The productivity of a stream is reflected in the insect fauna produced in the stream. Invertebrate productivity is strongly tied to the variety of habitats available to the benthos, as well as the food supply for the benthos. Riffle areas are the most productive stream areas in terms of invertebrate production. Within riffle areas, the greatest productivity occurs in water areas with rubble bottoms, depths from 8 to about 23 cm, and velocities between 33 and 46 cm/sec (1 to 1.5 ft/sec). In addition to being the most productive, these areas also produce the widest variety of species.

Riffle areas are more affected by reduced discharges than are pool areas, especially in terms of velocity across the riffle. Decreased velocity and increased sedimentation appear to be the two most critical variables in maintaining a productive and diversified invertebrate population. The overall effect of reduced discharges is likely to be a reduction in both the number and diversity of aquatic invertebrates produced in the stream.

These factors, in conjunction with reduced current velocities may result in the impoverishment of pool areas. Replenishment of the food supply in pools depends largely on the drift of invertebrates into the pools. Reduced productivity and lowered current velocities will tend to lower drift rates from riffle areas. Reduced diversity may result in a decrease in the size variation of resident invertebrates. This factor could have serious effects on fish species which rely on a gradation of food sizes as the fish grows.

Relatively little is known concerning the effects of reduced discharge on anchor ice formation during the winter. While anchor ice is a natural phenomenon, an increase in its extent, or the frequency at which it forms, could result in the catastrophic removal of increased numbers of benthos during the winter. Many species of fish essentially fast during the winter, and what is eaten is not well assimilated. An improvement in body condition during the spring is essential and requires a ready source of food. If food sources are depleted during the winter, spring mortality of stream fishes may be increased.

The balance of a stream fish population refers to the relative species abundance of a stream area. Reduced streamflow affects some species to a greater extent than others. Additionally, reduced discharges may affect a single species to a greater extent during a particular phase of its life cycle than during other times.

Species may be limited in their distribution by lack of suitable habitat, water quality parameters, reproductive potential, or through the inability to successfully compete with other species. Given the fact that under conditions of reduced discharge, velocity decreases faster than other hydrologic parameters, sediment deposition is enhanced, and summer water temperatures increase, it seems that species which can best tolerate these conditions will have a competitive advantage over less tolerant species. Therefore, it is possible for a good bass stream to become dominated by carp or other "rough" fish, even though stream conditions may be suitable, but marginal, for the bass. Each of the major changes in hydrologic variables resulting from reduced discharge appears to favor the production of coarse fish over other species at all stages of their life cycles.

Therefore, it seems reasonable that in order to maintain species equitability, the minimum conditions under reduced streamflow must be suitable, not just marginal, for the most sensitive species in the habitat. This sensitivity varies according to the phase of the life cycles of various species. The use of indicator fish species is suggested as a means of ensuring that all species will find conditions equally favorable or unfavorable. These indicator species must meet two general criteria: (1) they must be naturally present in the stream section under study during the period for which the flow recommendation is being made; (2) they must have well defined streamflow requirements which over-ride the requirements of all other species.

In purely trout habitats, any member of the salmonid family can be considered to be an indicator species. However, in a warm-water system, certain species are much more sensitive to the changes in hydrologic variables accompanying reduced discharges than are others. In addition, different indicator species would be used according to stream size (criterion #1) and according to phase of life cycle under study (criterion #2).

In large rivers, the migration and spawning recommendations may be made using the paddlefish as the indicator species. This species has the greatest passage requirement of all the species. According to Stockard (1907), the flow required for passage is equal to a suitable spawning flow for the paddlefish. This is convenient because areas of potential passage difficulties are more easily delineated than are potential spawning areas. For rivers in which the paddlefish does not reproduce, the sauger is recommended as the indicator species. This species also has restrictive migration and spawning requirements. The sauger is chosen over the walleye because it migrates earlier, and is somewhat more widely distributed than the walleye.

Rearing requirements in nearly all rivers of the Northern Great Plains may be determined by using the stonecat as the indicator species. This species is chosen for its restrictive velocity requirements, and its aversion to sedimentation. In addition, it is restricted primarily to those areas which are the most significantly affected by reduced discharges. Ensuring adequate flow for this species virtually guarantees an adequate flow for all others.

There may be over-riding considerations which must be determined before a minimum flow recommendation is made. Such over-riding considerations may require an in-stream flow which exceeds the flow requirement for the most sensitive indicator species for a particular biological function. For example, the effects of reduced discharge may result in summer temperatures in a given area which exceed the temperature tolerances of a species or species group, even though other habitat requirements are met for the indicator species. In this case, the flow requirement would be determined by maximum summer temperatures rather than by habitat considerations. Another case of an over-riding consideration might be the bank recharge requirements for riparian vegetation, or the discharge required to scour away colonizing vegetation. These discharges might easily exceed the flow requirements for the migration and spawning of the indicator species.

Ice formation during winter periods of lower discharge might endanger riffle productivity. Winter flows might need to be adjusted upward to maintain normal ice conditions. This would be an over-riding consideration.

The greatest over-riding consideration is the state of equilibrium between the inflow of sediment from the drainage basin, and the ability of the stream to remove such sediment. If all other conditions are met, but sediment deposition is accelerated in the stream, this condition will result in aggradation of the streambed with consequent deleterious effects applied to the stream community as a whole. It is strongly advised that any in-stream flow recommendation study include the installation of permanent, surveyed cross-sections, as described under the U.S. Geological Survey Vigil Network System (Emmett, 1956). The expressed purpose of the use of Vigil network sites is the continuous monitoring of the channel morphology to detect aggradation while remedial action may still be taken.

Riparian Vegetation

Riparian vegetation is here defined as both hydrophytic and phreatophytic vegetation growing on the floodplain and on river terraces. Its importance to the aquatic community has been briefly explained in earlier sections. Because this vegetation is dependent on a perennial supply of shallow groundwater, it is linked directly to streamflow. This constitutes an in-stream flow requirement, and justifies special consideration.

Riparian species are found where the plant roots are in contact with the water table throughout most of the growing season, or where periodic overbank stream flooding creates niches available for colonization by flood-tolerant species.

Phreatophytes are defined as plants which habitually obtain their water supply from the zone of saturation, either directly, or through the capillary fringe. The ground water supply may be either from ground water storage, or from surface water effluent into the ground water table. Hydrophytes require surface water or very shallow ground water (Robinson, 1956). Natural channel vegetation probably never reaches a climax due to floods, erosion, inundation, etc. As a result, mosaics of various seral stages with different dominant species characterize the vegetation communities (Campbell and Green, 1968).

Meinzer (1927) explains that depth to groundwater and persistance of groundwater as a year-round source are the two factors often governing plant species growing in a given area under semi-arid conditions. As the climate becomes more humid, this relationship breaks down, and the distinction is not so discernible. The depth to ground water is so important, that Meinzer states it is possible to estimate the depth to groundwater simply by noting the plant species growing in an area, and its associations with other plants.

Meinzer summarizes the depth to groundwater relationship in the southwestern United States as:

1) Rushes, sedges, cattails: These plants require water visible at the surface, or at most, very shallow groundwater. They indicate a perennial groundwater supply.

2) Reeds and cane (*Phragmites spp.*): Indicative of shallow, perenial ground water at depths up to 1.2 meters (4 ft).

3) Wheat or rye grass indicates groundwater from the surface to depths of 2.5 to 3.7 m (8 to 12 ft).

4) Salt grass (*Distichlis spicata*): In most places the average depth to groundwater is from .91 to 2.5 m (3 to 8 ft) below the surface. It rarely extends as far as 3 m (10 ft). Salt grass may occur exclusively, but is often found in association with rabbit brush (*Chrysothamnus graveolens*), greasewood (*Sarcobatus vermiculatus*), willow (*Salix spp.*), poplar (*Populus spp.*), or sagebrush.

5) Bunch grass (Sacaton: *Sporobolus airoides*): The capillary fringe probably extends to the surface, with water table depth of about a meter (a few feet). When associated with rabbit brush, the water table is probably never deeper than 3 to 4.6 m (10 to 15 ft). If the depth to groundwater is greater than 7.5 m (25 ft), the roots probably do not extend to the water table.

6) Rabbit brush (*Chrysothamnus graveolens*): Usually bordered on the channel side by a salt grass zone and on the terrace side by a greasewood zone. Depth to groundwater may range from .61 to 10 m (2 to 33 ft), but is more generally in the range of 2.5 to 4.6 m (8 to 15 ft). The most luxuriant growths occur where groundwater depth is about 2.5 m (8 ft).

7) Salt bush (*Atriplex spp.*): Observed water table depths ranged from 2.5 to 19 m (8 to 62 ft), with an average depth of about 8.5 m (28 ft).

8) Greasewood (Sarcobatus vermiculatus): Depth to water is usually from .85 to 12.2 m (2.7 to 40 ft). When associated with rabbit brush, the water table is between 2.5 and 4 m (8 and 12 ft) deep; with salt grass, between 1.2 and 2.5 m (4 and 8 ft). It grows most luxuriantly where the groundwater is between 3.1 and 6.2 m (10 and 20 ft) below the surface.

9) Alfalfa: Generally does poorly when the water table is near the surface. On non-irrigated land, the depth to groundwater is usually 1.8 to 4.6 m (6 to 15 ft), but one alfalfa plant was found with a tap root 39.4 m (129 ft) long.

10) Willow (Salix spp.): Water table is generally between surface 3.7 m (12 ft) in depth.

11) Cottonwood and poplar (Populus spp.): Cottonwoods indicate perennial, good quality water. The depth to groundwater is generally between 6.1 and 12.2 m (20 and 40 ft). Cottonwoods also require floods for the dissemination and germination of seeds.

The recommendation of a streamflow requirement for riparian vegetation will be perhaps the most difficult problem encountered. Robinson (1952) states that any phreatophyte may be killed by lowering the water table faster than the roots can follow it. Any disturbance which does not kill the roots results in regrowth. Bowie and Kam (1968) report that the water use of remerging and colonizing vegetation after deliberate vegetation removal, may be as great as that of the original vegetation.

Two possible results of channel dewatering may occur. The first is the rapid lowering of the floodplain and immediately adjacent groundwater table, resulting in theloss of primarily terrace vegetation, including most of the cottonwoods and other Populus species. The other is the rapid colonization and compacted zonation of the floodplain, and perhaps even the channel bottom. This will, in turn, result in a greater overall rate of transpiration, requiring a larger water supply. Conceivably, a flow requirement for fisheries might be released, or left in a stream, only to have it all absorbed by streamside vegetation. Yet, the streamside vegetation is so important in temperature regulation, cover, bank stabilization, and as a food source, that its removal or eradication would be disastrous both to the fishery and the wildlife habitat it helps maintain. Encroachment of vegetation onto the floodplain is not inherently bad. Burkham (1972) documented the encroachment of salt cedar onto the floodplain of the Gila River between 1917 and 1970. Prior to encroachment, the Gila River was around 610 meters (2000 ft) wide, shallow, braided, and had a sinuosity ratio of about 1. Encroachment of salt cedar started shortly after 1917, and in 1968, the channel was less than 60 meters (200 ft) wide, with the sinuosity ratio increasing to about 1.2. The result has been the stabilization of the floodplain and channel.

Of the two possibilities, encroachment and compacted zonation appear to be the most likely. Lowering of the water table at the rate required to kill plants would probably require pumping. However, at the margins of the floodplain and terrace, it is likely that most or all the deep rooted trees will die due to desiccation. This would be caused by insufficient recharge of the groundwater system during the spring runoff.

Groundwater recharge is dependent on many factors, many of which are discharge related. Surface area covered by water has a major influence in the rate of seepage. As greater areas are covered with water, the rate of infiltration increases. Depth of water is also important. Deeper water exerts a greater downward force (head force) than does shallow water, because of its greater mass per unit area. Velocity of streamflow is perhaps the most important aspect in recharge of subsurface water in alluvial channels. Burkham (1970) explains that the beds of most alluvial channels are not structurally stable. That is, during some flow events, some movement and rearrangement of bottom materials occurs which effect infiltration rates by changing the permeability. In most alluvial channels, the silt and clay fraction of the surface layer are set in motion as the stream velocity increases and settle to the bottom as velocity decreases, leaving the finest and least permeable materials on top. At the onset of a short duration event, such as a thundershower, the infiltration velocity is slower because of the fines left on the bottom by preceeding flows. As the fines begin to move, the infiltration rate increases during the ascending limb of the flow event, and decreases as the fines settle during the recession of the flow. Therefore, infiltration velocity would be linearly related to velocity as well as stream depth.

To an extent, the rate of evapotranspiration determines the rate of infiltration from the stream into the groundwater table by increasing the hydraulic gradient away from the stream. For the most part, however, the rate of infiltration is a hydrologic function. In order for riparian vegetation to survive, the rate of infiltration must be equal to the rate of evapotranspiration during the growing season. The rate of both vertical and horizontal seepage is a function of wetted area, depth, and velocity. Therefore, there is a close relationship between discharge and potential evapotranspiration (Coffin, 1968).

The effects of reduced discharge on riparian vegetation, then, will likely be a compression of seral stages away from the stream. The negative impact on vegetation close to the stream will probably be minimal, and in the absence of disturbing floods will actually be favorable to growth. The effects will be most noticeable at some point away from the river where the permanent water table falls to a point below the roots of the plants. These effects will likely be most detrimental to local ranchers whose alfalfa crops lie on these subirrigated floodplains and terraces. The potential for local economic losses deserves a great deal of study and consideration.

MINIMUM DISCHARGE RECOMMENDATION METHODOLOGIES

A wide variety of methods is available for use in recommending the discharge needed for the perpetuation of the resident fish community. These methods vary not only in difficult and reliability, but also in the criteria used in the decision making process. Some of the methods presented are designed specifically for the purpose of determining the discharge required for the spawning of anadromous fishes. Others are designed for the recommendation of discharges to meet water quality needs alone. However, several of these methods are fully applicable for the determination of other biological functions by simply changing the criteria used. This section is an intensive review of representative methodologies in current use, and includes a discussion of the limitations of the different methods.

Methods using field measurement and biological criteria

California

The basis for present day evaluation and recommendations of stream flows for resident trout as used by the California Department of Fish and Game was established in late 1960. The procedures appear to follow those of Curtis (1959) in his studies of the Pit and Feather Rivers. Curtis selected 40 cross sections at 305 meter (1000 ft) intervals along the stream. It was believed that site randomization could reasonably be accomplished by establishing transects at exact 305 meter intervals, regardless of the ease and convenience of moving the site several feet in either direction (because of vegetation or bank conditions). Hydrologic variables such as wetted perimeter, maximum depth, bottom area, and average velocity were measured and plotted against discharges of 1.4, 2.8, 4.2, 5.6, and 7.0 cubic meters per second (50, 100, 150, 200, and 250 cfs). For comparison with high discharge data, the Pit River was also surveyed at 40 cross-sections at a discharge of 98 cubic meters per second (3500 cfs). It was found that water velocity changed at the greatest rate with decreasing discharge. Wetted perimeter, bottom area, and depth decreased much more slowly than did discharge (Curtis, 1959).

In 1960, the California Department of Fish & Game proposed a method for investigating the volume of flow required by trout below dams (Hooper, 1973). The method considers that the most basic requirements for trout, besides space, are spawning area, food, and shelter. Criteria established for California streams are:

1. Food production: Gravel to rubble bottom; 15.2 to 91.5 cm per second velocity (0.5 to 3.0 ft/sec); and depths from 2.5 cm to 91.5 cm (1 inch to 3 feet).
2. Shelter: Any place where an adult or catchable-sized trout will return to when frightened or disturbed.
3. Spawning area: Pea-sized to 7.5 cm gravel; velocity range of 15.2 to 91.5 cm/sec (0.5 to 3.0 ft/sec); and depths ranging from 7.5 cm to 91.5 cm (3 inches to 3 feet).

When areas of food production, shelter, and spawning were graphed for each discharge, the shapes of the curves were similar. Major findings of the study of Taylor Creek, near Lake Tahoe, were that as the flow decreased:

1. The percent loss in food and shelter is greater than the percent loss in cross-sectional or surface area of water.

2. The rate of loss in food and shelter increased as the flow decreased over the range of flows studied.
3. The cross-sectional area and surface area of water decreases at a much slower rate than the volume of flow (Hooper, 1973).

Oregon

The Oregon State Fish Commission utilizes an intensive field measurement approach, coupled with flow criteria for migration, spawning, incubation, and rearing.

To determine the flow recommendation for migration in a given stream, the shallow bars most critical for passage of adult fish are located. A transect is established which follows the shallowest course from bank to bank. At each of several discharges, the total width and the longest continuous portion of the transect meeting minimum depth and maximum velocity criteria are measured. For Chinook salmon, for example, the minimum depth criterion is about 24 cm (0.8 ft), and the maximum velocity criterion is 2.4 meters/second (8.0 ft/sec). The total usable width and the longest continuous usable portion of each transect are each plotted against discharge. The recommended flow for passage is that discharge which meets the criteria on at least 25% of the total transect width and has a continuous usable portion equalling at least 10% of the total transect width. Table 9 and Figure 2 illustrate the use of transect data for the determination of passage flow requirements.

In the determination of recommended spawning discharges, three gravel bars are selected which represent the typical dimensions of those occurring in the study area. A transect is marked across each bar where

TABLE 9

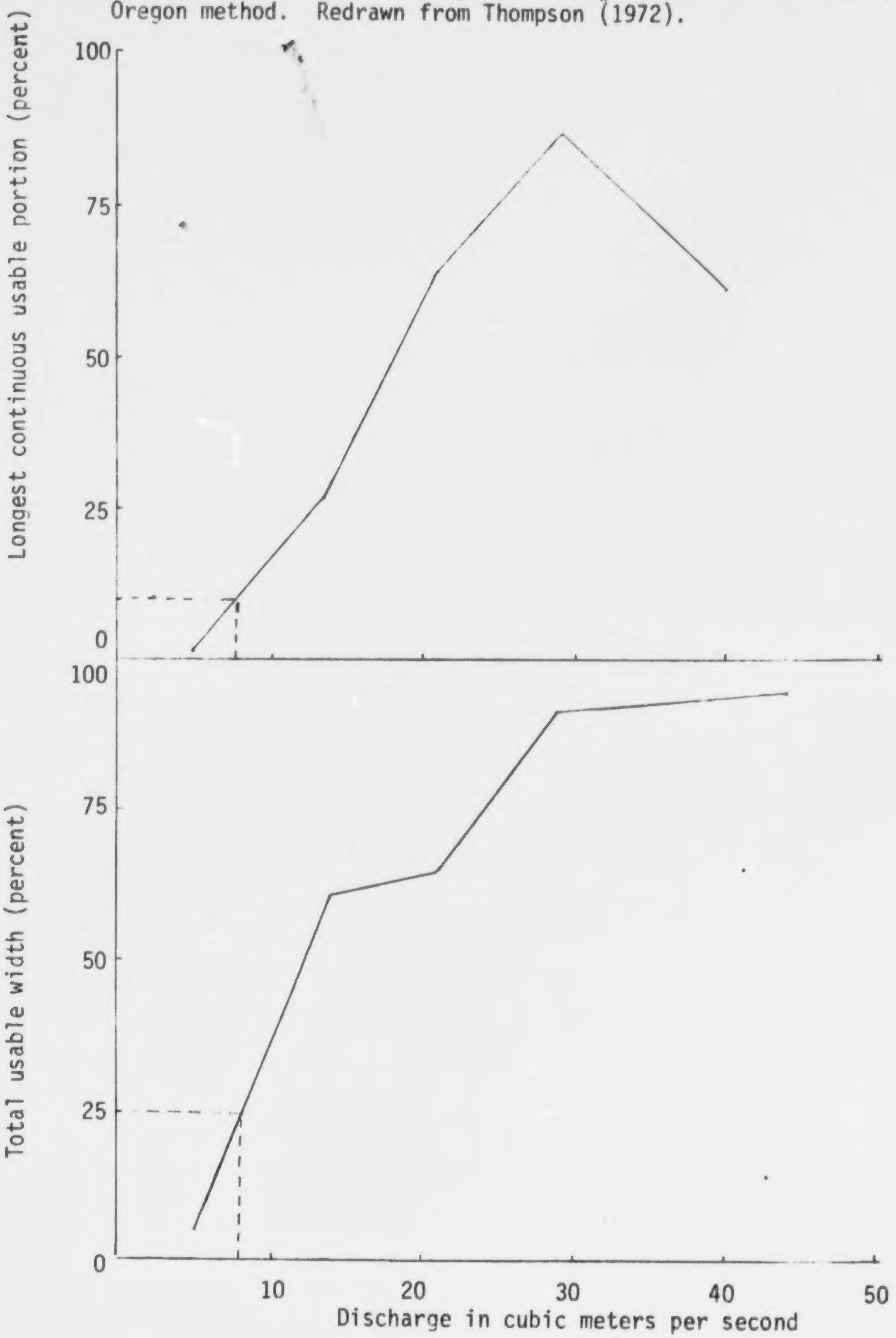
PASSAGE CROSS SECTION DATA, OREGON METHOD *

Flow	Total width	Wetted width	Usable width		Longest continuous usable width	
(cms)	(meters)	(meters)	(meters)	(%)	(meters)	(%)
5.3	305	140	6.7	4.8	3.5	1.2
29.0	305	250	230	92.0	220	88.0
44.0	305	305	290	95.0	189	62.0
20.6	305	296	192	65.0	192	65.0
13.4	305	246	149	61.0	93	26.6

From: Thompson, Kenneth. 1972. "Determining Stream Flows for Fish Life," in Proceedings of the Instream Flow Requirement Workshop, Portland, Oregon, March 15-16, 1972, pp. 31-46.

* Data converted to metric units.

Figure 2: Example of data plot for migration flow recommendation-Oregon method. Redrawn from Thompson (1972).



spawning is most likely to occur. At each of several discharges, the portion of the total transect length which meets both depth and velocity criteria for the species studied is measured. The stream width which is usable for spawning is then plotted against discharge. The optimum spawning discharge is that which provides the greatest usable width along the transects. The recommended guidelines of the Oregon State Game Commission state that the minimum spawning flow is that discharge which meets spawning criteria over 80% of the usable width of the transect.

This type of analysis is termed by Sams and Pearson (1963), the "usable width analysis." These researchers have developed a "weighted usable width analysis" which gives more significance to areas which are used more extensively for spawning than others. The basic premise of this method, is that portions of the transect with only 2% of the redds should not be given the same value as those widths having velocities containing 30% of the redds. This refinement distinguishes between usable and preferred conditions. Thus, velocities at the upper and lower limits of the spawning criteria for velocity are weighted by a factor reflecting the relative preferences for velocities within the criteria range. Each portion of the total stream width within a certain velocity range is multiplied by this preference factor, giving unit weight to the most preferred velocity range. Weighted sections are then added together to obtain the weighted usable width of each transect. After the weighted usable width has been determined for each discharge, a curve is drawn against discharge for the flow recommendation.

The Oregon method is much less precise for the determination of flows during the incubation and rearing stages. The relationship which surface flows have with the intra-gravel environment may vary from stream to stream. Among the considerations during the incubation period are wetted perimeter, intra-gravel and boundary layer water velocity, dissolved oxygen concentration, sedimentation, and temperature (Hoppe and Finnell, 1970; Silver, Warren, and Doudoroff, 1963; Vaux, 1968; Wickett, 1954). In Oregon, the flow required to cover spawning gravel areas and to maintain suitable intra-gravel conditions for fry development is estimated by field observations of each stream. In general, this discharge averages about 2/3 of the spawning flow (Thompson, 1972).

Rearing is loosely defined as the period when fish are not migrating or spawning, and eggs or fry are not in the gravel. Rearing is probably the most poorly understood and most critical period of time of survival to the fish. Important considerations for the rearing period are food production, cover, flow stability, stream velocity, water quality, and space (Fraser, 1971; Chapman, 1966a). The criteria used by Oregon for the recommendation of rearing flows include:

1. "Adequate" depth over riffles.
2. Pool-riffle ratio of 50:50.
3. Riffle areas approximately 60% covered.
4. Riffle velocities of 30 to 45 cm/sec (1.0 to 1.5 ft/sec).
5. Pool velocities between 9.1 and 24.4 cm/sec (0.3 to 0.8 ft/sec).

Washington

The Washington Department of Ecology recommends the use of an alternative matrix for evaluating and displaying the impacts of alternative low discharges. Included in this matrix are fishery needs (migration, spawning, incubation, and rearing capacity); recreation needs (swimming, canoeing, and kayaking, and fishing); and water quality needs (primarily waste assimilation capacity) (Bishop and Scott, 1973).

In-stream requirements for fisheries are evaluated by a methodology designed by Collings (1972). Study site selection is determined by the representation by a particular stream of the drainage net as a whole. Priorities are given to those streams on which development projects are imminent.

The spawning requirement methodology was developed from fishery data collected from each of eighteen streams. Each stream contained three study sites, with four cross sections measured at each site. To obtain a sample, the discharge is measured, the river stage noted, and the depth and velocity measured at 10 to 25 points on each cross section. All velocities are measured 12 cm (0.4 ft) from the streambed. Cross sectional depth and bottom velocity for each discharge are then plotted on separate planimetric maps of each study reach at each discharge. Isolines of equal depths and velocities are then drawn on the maps.

After this stage is completed, depth and velocity criteria for each species are determined, and areas of preferred spawning depth and velocity can be delineated on the map. Figures 3 and 4 demonstrate the use of preferred area maps. Areas containing both preferred depth and velocity ranges are shaded in on a composite map (Figure 4), and defined as the optimum spawnable area for the reach at a given discharge.

The area of optimal spawning grounds is then plotted against the measured

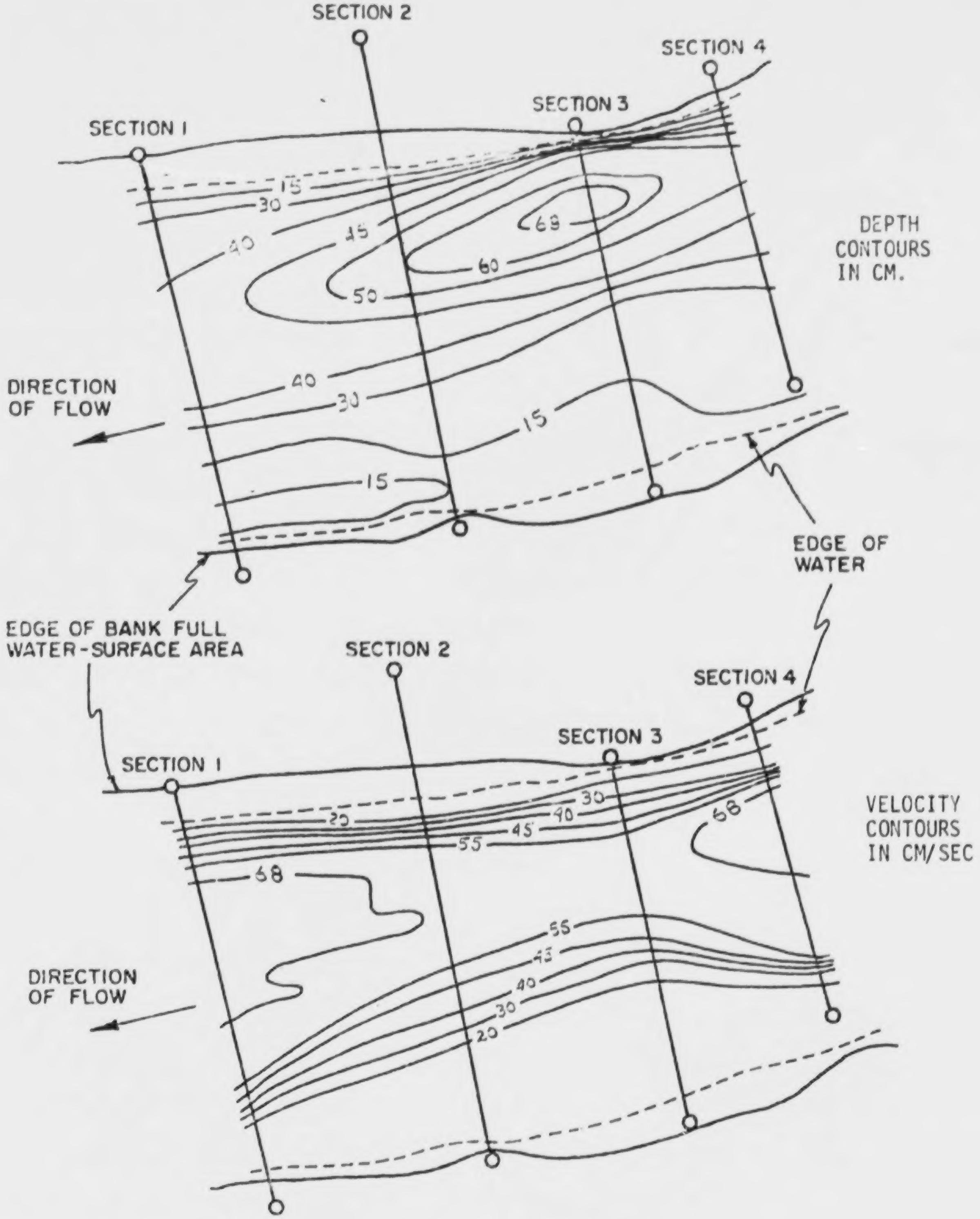
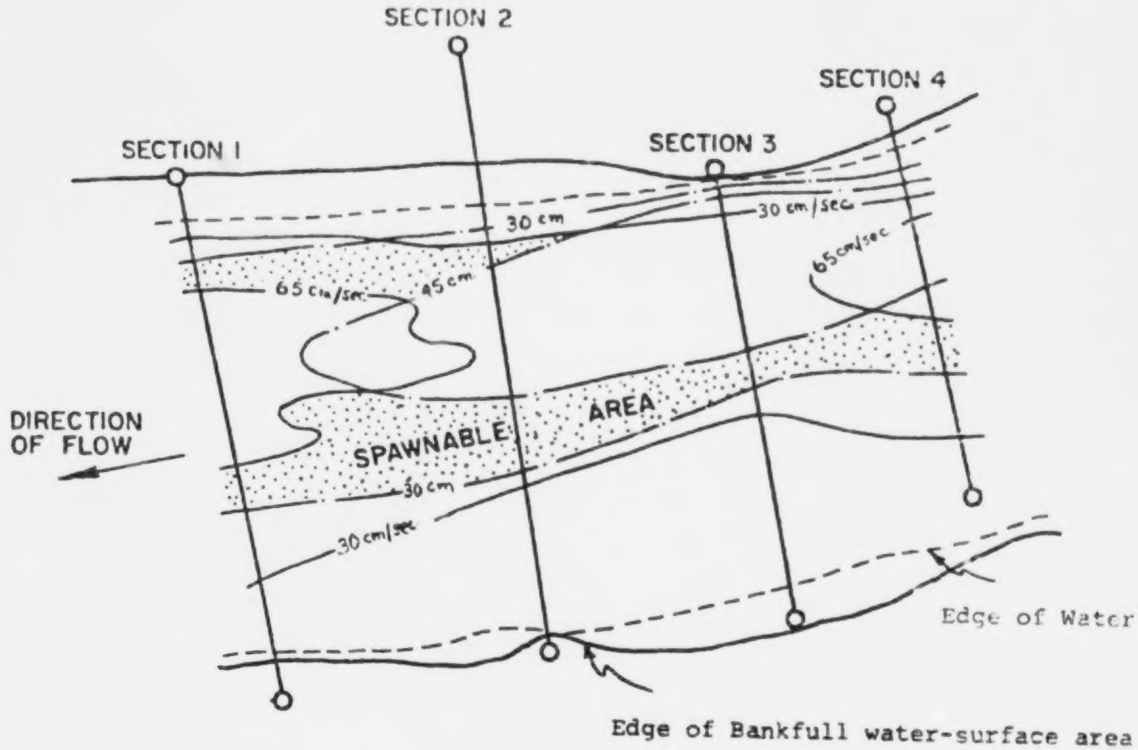

SECTION 2
SECTION 4
SECTION 3
SECTION 1
15
30
40
45
68
60
50
DEPTH CONTOURS IN CM.
40
30
15
15
DIRECTION OF FLOW
EDGE OF WATER
EDGE OF BANK FULL WATER-SURFACE AREA
SECTION 2
SECTION 4
SECTION 3
SECTION 1
30
40
20
45
55
68
68
VELOCITY CONTOURS IN CM/SEC
55
45
40
30
20
DIRECTION OF FLOW

Figure 3: Example of planimetric view of study reach, showing transects, and depth and velocity contours. From Bishop, Robert and Scott, James. 1973. "The Determination and Establishment of Minimum Stream Flows in Washington State," Washington State Department of Ecology, Draft Report No. 73-033., Olympia, September, 1973. 80 pp.

Figure 4: Example of composite planimetric map of a study reach, with the area of preferred spawning habitat shaded.


SECTION 1
SECTION 2
SECTION 3
SECTION 4
30 cm
30 cm/sec
65 cm/sec
45 cm
65 cm/sec
DIRECTION OF FLOW
SPAWNABLE AREA
30 cm
30 cm/sec
Edge of Water
Edge of Bankfull water-surface area

RESULTS:

DISCHARGE; 1.9 m^3/sec

PREFERRED DEPTH AREA; 105 m^2 , BETWEEN 30 - 45 cm

PREFERRED VELOCITY AREA; 171 m^2 , BETWEEN 30 - 68 cm/sec

AREA PREFERRED FOR SPAWNING; 72.6 m^2

From: Bishop, Robert and Scott, James. 1973. "The Determination and Establishment of Minimum Stream Flows in Washington State," Washington State Department of Ecology, Draft Report No. 73-033, Olympia, September, 1973. 80 pp.

discharge (Figure 5). The preferred spawning curve rises to a peak, or optimum discharge, which is easily distinguished. Minimum or sustained spawning discharge is defined as about 75% of the optimum spawning discharge.

The Washington method does not develop criteria for incubation or migration, but does include a section for the determination of rearing flows. The guidelines for rearing criteria are about the same as those used in the Oregon method, but measurements of several hydrologic relationships are added. Figure 6 shows the relationships of these variables to discharge.

Other methods using field measurement

Two additional methods which utilize biological criteria and field measurement have been developed by Sams and Pearson (1963). Both methods utilize less measurement and more calculation than the methods presented previously.

"Two or more flow method"

In this method, cross sections are selected across spawning areas, and a staff gage installed at each cross section. A discharge determination is made at one cross section for two or more flows in order to construct a rating curve of discharge vs. gage height for all intermediate flows. At each of the other stations, the cross sectional areas are determined for the same discharges entered on the rating curve and the water level on each staff gage is noted. Rating curves are then constructed for cross sectional area of each station vs. gage height at the station. From these data it is possible to determine the average velocity across

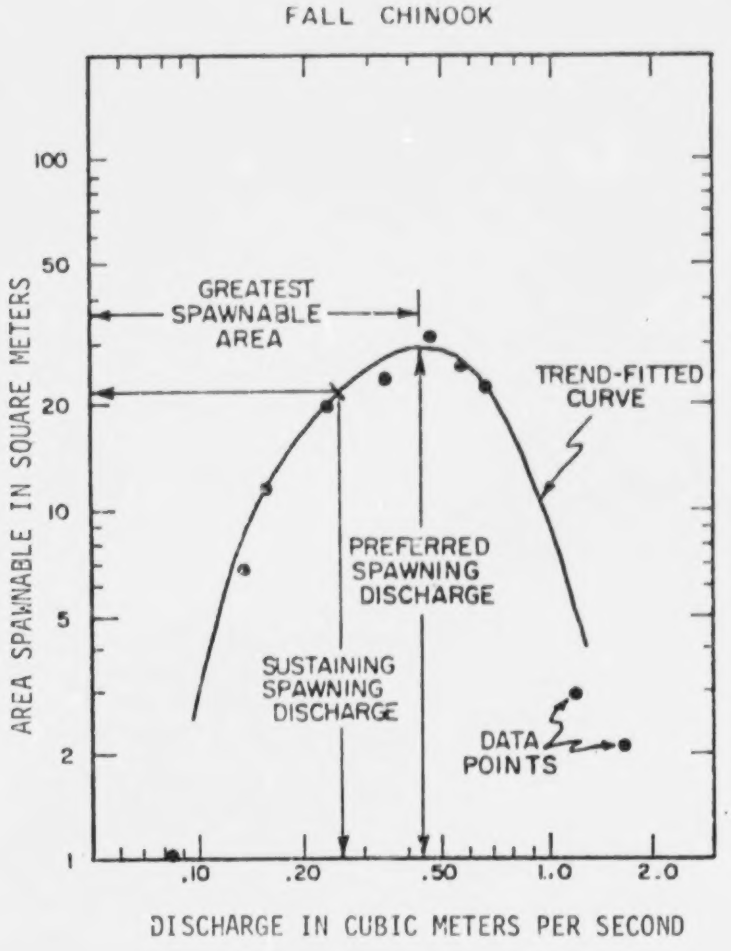


Figure 5:
"PEAK OF CURVE" METHOD TO SELECT THE PREFERRED SPAWNING DISCHARGE.

From: Bishop, Robert and Scott, James. 1973. "The Determination and Establishment of Minimum Stream Flows in Washington State," Washington State Department of Ecology, Draft Report No. 73-033, Olympia, September, 1973. 80 pp.

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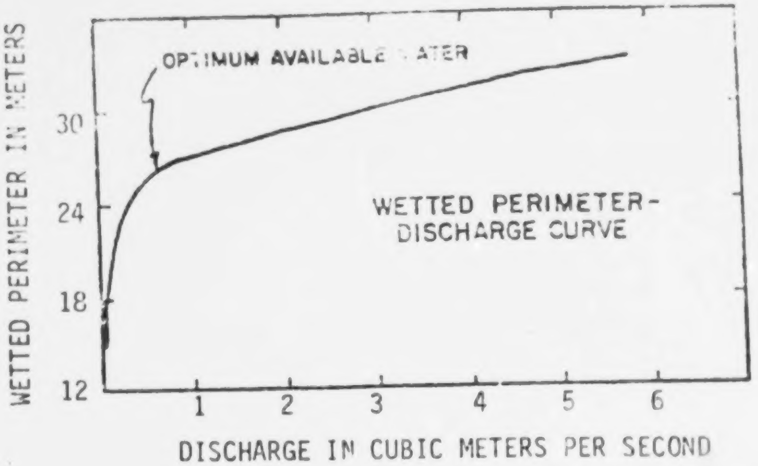
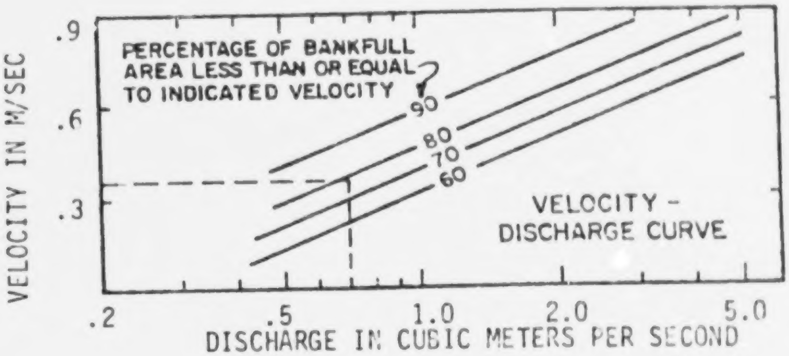
PART A:

WETTED PERIMETER
VERSUS
DISCHARGE



PART B:

WATER VELOCITY
VERSUS
DISCHARGE



ARBITRARILY SELECTED DISCHARGE (M/SEC)	PERCENTAGE OF BANKFULL AREA FOR:		PERCENTAGE OF BANKFULL AREA HAVING VELOCITIES BETWEEN 31 and 37 cm/sec
	31 cm/sec	37 cm/sec	
1.0	60	65	5
.7	71	79	8
.5	82	86	4

PART C:

WATER DEPTH
VERSUS
DISCHARGE

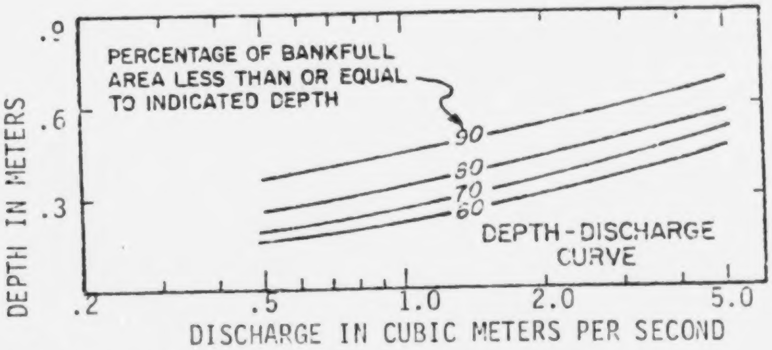


Figure 6: Example of curves for the determination of rearing flow. From: Bishop, Robert and Scott, James. 1973. "The Determination and Establishment of Minimum Stream Flows in Washington State," Washington State Department of Ecology, Draft Report 73-033, Olympia, Sept., 1973.

individual transects at any given intermediate flow. The measured flows and calculated intermediate flows are then analyzed by averaging the calculated velocities from all cross sections and constructing a curve with average velocity on the abscissa and discharge on the ordinate. The water velocity is measured over a number of redds of a particular species, and an average "preferred" velocity obtained. This average velocity is located on the velocity-discharge curve. The optimum spawning discharge is that giving the preferred average velocity on the curve.

"One flow method (using average stream width)"

A one-mile reach of stream is selected which best represents the stream as a whole, particularly the part used for spawning. Cross sections are established at 31 meter intervals (100 ft), and the width of the stream is measured at each cross section.

The average stream width and the average pool widths are calculated separately. If the average stream width is about the same as the average pool width, the method may be used safely. If they differ significantly, there is sufficient variability in the channel morphology to invalidate figures obtained by the method.

Depths and velocities are measured over as many redds as possible within the stream section, and average depths and velocities calculated for all the redds. The average pool width, multiplied by the average depth and average velocity of water measured over the redds gives the optimum spawning discharge by Q = W x D x V.

A method using observation and experience

The "Montana method"

Tennant (1972), after many years of observing stream flows and the fishery potential at those streamflows, developed the "Montana method" of minimum streamflow determination. These determinations are the result of years of stream observation, and the use of professional judgement concerning the adequacy of various discharges to meet the needs of the fish community. Observations and data collections were made at reaches of streams near a U.S. Geological Survey gage house, where the discharge could be noted at the time of observation.

When the discharge which was considered to be adequate was compared to the streamflow records of the stream, it was usually found to be about 30% of the mean annual flow. This 30% figure was reached after applying this procedure to a large number and variety of streams. From these findings, the Montana method suggests that any flow over 30% of the mean annual flow can be considered a satisfactory flow for rearing. The Montana method suggests that the minimum flow for the period October to March, should be at least 30% of the mean annual flow. For the critical spawning and summer periods (April to September) a flow of 60% of the mean annual flow is recommended to ensure adequate migration and spawning flows. This method considers a discharge of 10% of the mean annual discharge to be at best a short time survival flow.

The Montana method has been field tested in respect to suitable rearing conditions by several researchers. Wesche (1973) found that all hydrologic variables changed at the greatest rate for the discharge interval of 25% to 12.5% of the average daily flow.

Kraft (1968, 1972) studied the effects of three separate dewaterings (25%, 50%, and 75% of mean low flow) on a Montana trout stream. At 75% dewatering, production and migration to pools was about the same as in control sections. At 90% dewatering, riffle areas were nearly totally exposed, leaving only pools. Trout in the runs decreased 62% by number and 53% by weight, while pools in the dewatered reach showed an increase in both numbers and weight as the fish retreated into them. Both temperature and sedimentation increased at reduced flows, even though the study reach was relatively short. The study period was probably not long enough to determine the long term effects of a 75% dewatering.

An application of the Montana method to a stream in Oregon resulted in a rearing flow recommendation similar to that found using the more extensive Oregon method, but was considered invalid for use in western Washington when compared with the Washington method (Bishop and Scott, 1973).

Methods using various flow related formulae

Bureau of Sport Fisheries and Wildlife

The Billings, Montana office of the Fish and Wildlife Service (Bureau of Sport Fisheries and Wildlife) used a synthetically developed approach in the Northern Great Plains Resources Program (NGPRP) for deriving preliminary instream flow need estimates for selected streams and rivers in eastern Montana and eastern Wyoming. The approach pertained only to the NGPRP and was a technique employed to meet the commitments of the study. The procedure was not used on streams and rivers with extremely erratic and fluctuating flow conditions.

The instream water estimate is based on the premise that any flow recommendation should be made for each month in terms of the flow regimen of an average water month. These months are delineated from abnormal months and subnormal months, thereby eliminating extreme conditions. The average water months (as applied to a specific month for the period of record) are selected by first finding the mean monthly flow for the entire period of record for a given stream reach. Flows to be contained in the average water month category are then delineated from wet and dry months by using the following statistical approach:

1. The standard deviation for the period of record is determined.
2. The Student's value for n-1 year's of record and a given level of probability (here 30%) are obtained.
3. Confidence limits are established by multiplying the standard deviation for the data, by the "t" value for the level of probability.
4. The interval delineating the months to be included in the average grouping is the mean of the period of record, ± the confidence limits. Months in which the streamflow falls outside this interval are not used in the computations.

The daily flows for all the months in the average category are then arrayed from the lowest to highest. The estimated in-stream flow requirement is defined as the discharge which is exceeded 90% of the time for the time segment under study.

This 10-percentile flow is then considered the base-line estimate of in-stream needs. If necessary, the figure is modified to account for water entering or leaving the stream within the study reaches, the type of fishery and riparian resources and specific species requirements (Wood, 1974).

"The one-flow method" (using flow predicting formulae)

In this method, several cross sections are selected over good spawning areas. At each cross section, depth and velocity are measured. With a transit and rod, the approximate location of the edge of the water at two higher flows above the measured base flow is determined. The cross-sectional area of these projected flows is then measured. The discharges for each of the measured areas are then found by one of the following flow predicting formulae:

1. If the base flow has an average velocity greater than 33.6 cm/sec (1.1 ft/sec);

$$Q = K\ D\ (1 + W/10)^{3/2} \tag{1}$$

2. If the base flow has a velocity of 27.2 to 33.6 cm/sec (0.9 to 1.1 ft/sec);

$$Q = K\ D\ (1 + W/10)^{5/3} \tag{2}$$

3. If the base flow has a velocity less than 27.2 cm/sec (0.9 ft/sec);

$$Q = K\ D\ (1 + W/2A)^{5/2} \tag{3}$$

Where,

Q = discharge in cubic meters per second (cubic feet per second)

D = average depth of cross section in meters (feet)

W = change in width per 3 cm (.1 ft) rise from the base flow to the predicted flow

A = cross sectional area at the predicted flow level

K = an empirical constant; found by dividing the base flow by the average depth at base flow to the 3/2, 5/3, or 5/2 power, whichever is appropriate from the velocity categories.

The object of the calculation is the determination of the discharge and cross sectional area of each transect from projected data taken at low flow. After the flows at each level have been calculated, rating curves of cross sectional area vs. discharge are made, and the average velocity of each section determined. This average velocity is then used in the average velocity analysis as described under the "two or more flow method." (Sams and Pearson, 1963)

Methods relating streamflow to cover

Wesche (1973) has developed a method of analyzing usable cover for brown trout, which could easily be applied to other species which show cover preferences and to streams having overhanging vegetation and undercut banks. Wesche's method utilizes a cover rating determined from cover criteria obtained from fish captures in different cover types. The cover rating, CR, is found by the use of the formula:

$$CR = \frac{L\ ucb}{T} \times (PF\ ucb) + \frac{A}{SA} (PF\ a) \tag{4}$$

Where,

L ucb = length of undercut banks in the stream section having a water depth of at least 15 cm and width of at least 9 cm.

T = length of the thalweg line through the stream section.

A = surface area of the stream section having a water depth of at least 15 cm and a substrate size of 7.5 cm or greater.

SA = total surface area of the stream section at the average daily flow.

PF ucb = preference factor of brown trout for undercut banks.

PF a = preference factor of brown trout for instream rubble-boulder areas.

The above preference factors are determined by the number of fish captured in cover types of one or the other kind, divided by the total number of fish captured. For example, if 85% of the captured fish were using undercut banks for cover, the preference factor, PF ucb, would be 0.85.

Boussu (1954) analyzed the relationship between cover and trout production by both the addition and clearing of streambank vegetation. He used planimetric maps to determine the areal change in cover to each section of stream altered. The advantage of Boussu's method lies in its use of areal units rather than rating. A rating, by including many factors at once, may tend to mask the importance of the various parameters comprising the rating.

A modified method for analyzing cover might include the better aspects of both methods. Cover could be determined in absolute values for a given discharge, divided into cover types (including depth of water and current velocity), and a preference factor applied to those cover areas which appear to be preferred by the stream fish. This would be a "weighted area" method, which would give results in terms of preferred cover area as a function of discharge.

Methods relating streamflow to water quality

Temperature

Peterson and Jaske (1970) have developed a sophisticated mathematical model to simulate thermal effluent in an irrigation system. If all the inputs into the model can be determined with a fair degree of accuracy, the model gives good results when compared with empirical results. The heat budget for a given section of river is given by equation 5.

$$\sum Q = Q_t = (Q_s - Q_r) - Q_b - Q_e \pm Q_h + Q_v \qquad (5)$$

where,

Net insolation,

Q_s incoming solar radiation

Q_r = reflected short wave radiation from the water surface

Back radiation

$$Q_b = 2.62\ \sigma\,(T^4_w - \beta T^4_a)\ \text{Kcal/m}^2\text{/hr} \qquad (6)$$

σ = Stefan Boltzmann radiation constant

β = atmospheric radiation factor derived from cloud cover and vapor pressure

T_w = temperature of water surface in ^oK

T_a = temperature of air in ^oK

Evaporation

$$Q_e = 37.2\ u\ (l_w - l_a)\ \ \text{Kcal/m}^2\text{/hr} \qquad (7)$$

u = wind speed in km/hr

l_w = vapor pressure in mm Hg

l_a = vapor partial pressure in mm Hg

Conduction

$$Q_h = 0.0126\ k\ p\ u\ (t_a - t_w)\ \text{Kcal/m}^2\text{/hr} \qquad (8)$$

k = correction factor varying between 1 and 3 for rapid streams

p = atmospheric pressure in mm Hg

t_a = mean air temperature in ^oC

t_w = mean water surface temperature in ^oC

Advected energy

Q_v = term used to input discharge heat from thermal effluents, and in special cases handle ice, etc.

The temperature for a section is determined by means of equation 9:

$$T_w = \left[\frac{1}{V_r} \; \frac{Q_t A}{62.5} + V_i \, (T_i - T_w) \right] \tag{9}$$

where,

V_r = mean river section volume

Λ = mean river section surface area

= time increment

V_i = inflow volume per time increment

T_i = mean temperature of inflowing water

T_w = mean temperature in a given section of river

Q_t = net heat transport per time increment

The authors explain that the above method applies to homogeneous, isotropic media. It can be modified for nonhomogeneous media by incorporating it into a computational system which uses intermittent transport and mixing with respect to the ratios of mean travel times of water masses through a fixed volume. The computational form used in this study assumes a flow system composed of an inner fast-moving trough and a slower outer trough. This approximates the velocity distribution through the water column. The inner trough is assigned the notation B, and the outer trough the notation 1 - B. The model sets up a series of difference equations and repeatedly computes the downstream temperatures as a function of the input data such that:

$$T_{i+1,\, j+1} = (1-B) \left(T_{i,j} + T^1{}_{i,j} + T^2{}_{i,j} + B \quad T_{i,j-1} + T^1{}_{i,j-1} + T^2{}_{i,j} \right) \tag{10}$$

where,

$T_{i,j}$ = average water temperature of the beginning of the jth flow increment at the end of the ith time increment (flow day) in ^{o}C.

$T^{1}_{i,j}$ = temperature change during the first half of the ith time interval in the jth flow increment as determined from surface heat exchange plus advected energy in ^{o}C.

$T^{2}_{i,j}$ = same as above except for the second half of the ith time interval.

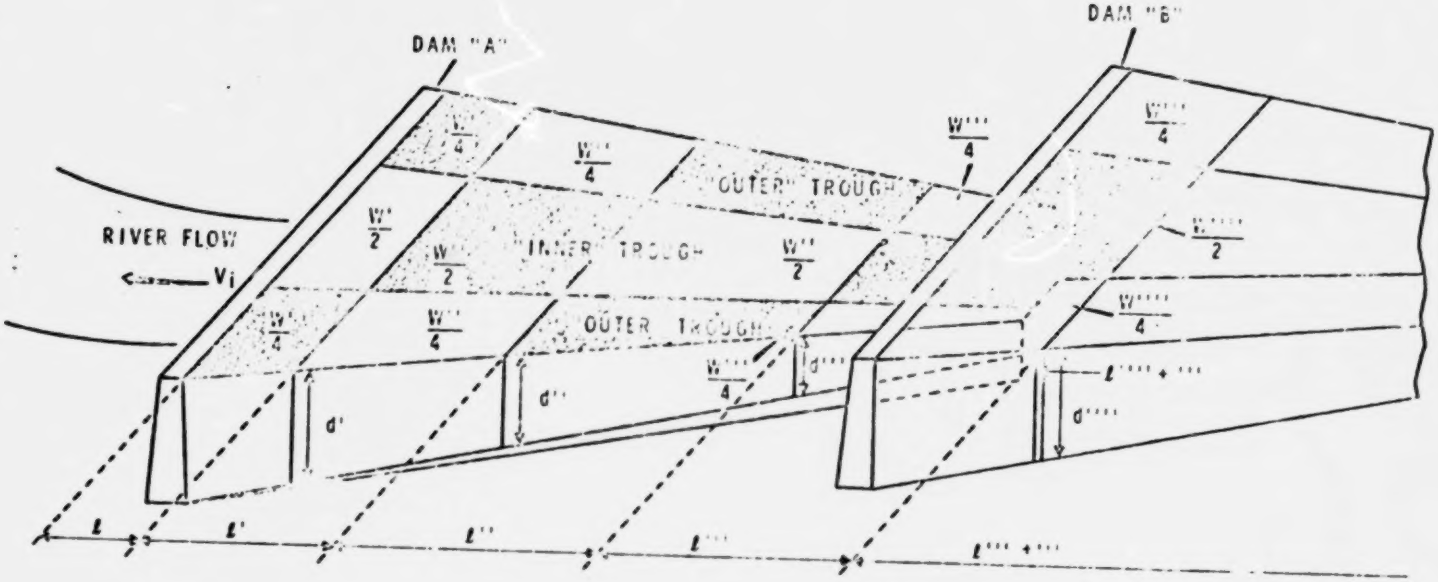
B = the fractional part of the water in the inner fast-moving trough.

At the end of the ith time interval the water in the inner and outer troughs of each section is mixed and an average temperature for the section is calculated. The procedure is then repeated for the i + 1 interval. Operation of this model requires the following data and manipulation:

1. River dimensions must be reduced to equivalent non-parallel trapezoidal cross sections. See Figure 7.
2. Water temperatures at the upstream end of the reach under study, and also at downstream locations,
3. Streamflow at inlet and outlet of each stream section,
4. Meteorological data over area of interest (wind velocity, mean air temperature, dew point, sky cover, incoming solar radiation),
5. Advected heat quantities.

Dissolved oxygen

The State Department of Ecology at Olympia, Washington, uses a four-level of intensity modeling scheme. The intensity level used determines the accuracy and degree of resolution of the results, and also determines


DAM "A"
DAM "B"
RIVER FLOW
V_i
$\frac{W'}{4}$
$\frac{W'}{2}$
$\frac{W'}{4}$
$\frac{W''}{4}$
$\frac{W''}{2}$
$\frac{W''}{4}$
"OUTER" TROUGH
"INNER" TROUGH
OUTER TROUGH
$\frac{W''}{2}$
$\frac{W'''}{4}$
$\frac{W'''}{4}$
$\frac{W''''}{4}$
$\frac{W''''}{2}$
$\frac{W''''}{4}$
d'
d''
d'''
d''''
ℓ'''' + '''
ℓ
ℓ'
ℓ''
ℓ'''
ℓ''' +'''

ℓ VARIES AS RESERVOIR GEOMETRY AND FLOW
AND REPRESENTS A RESERVOIR LENGTH FOR THAT REGION
ONE FLOW DAY IN LENGTH

Neg 0695417

Figure 7: Model of Channel Flow at a Translational Instant

From: Peterson, D.E. and Jaske, R.T., 1970. Simulation Modeling of Thermal Effluent, Battelle Memorial Institute, AEC R & D Report # BNWL-1277.

the cost and manpower involved.

An example of a low level dissolved oxygen model is offered in figure 9. These curves provide a generous flow and allow for error on the high side. The maximum estimate of low flow can be an order of magnitude too high. However, this type of a graph can be extremely useful in predicting the potential of a dissolved oxygen problem, based on the waste loading.

If a problem is likely, as indicated by the available flow and the waste loading determined by Figure 8, a more detailed analysis is probably warranted. This would require one of several modifications of the Streeter-Phelps model of the decay of carbonaceous materials. The generalized form is given in equation 11.

$$\frac{dc}{dt} = \frac{-1}{A}\frac{d}{dx}(OC) - K_d L - K_n L_n + K_a(c_s - c) - S_b + P - R + C_r\left[\frac{dQ}{d^{x}}/A\right] \qquad (11)$$

where,

c = dissolved oxygen concentration

c_s= dissolved oxygen concentration at saturation

c_r= dissolved oxygen of flow added along the river

S_b= dissolved oxygen sink due to sludge deposition

P = dissolved oxygen added by photosynthesis

R = dissolved oxygen sink due to plant respiration

K_a= atmospheric reaeration coefficient

K_d= deoxygenation coefficient for carbonaceous waste

K_n= deoxygenation coefficient for nitrogenous waste

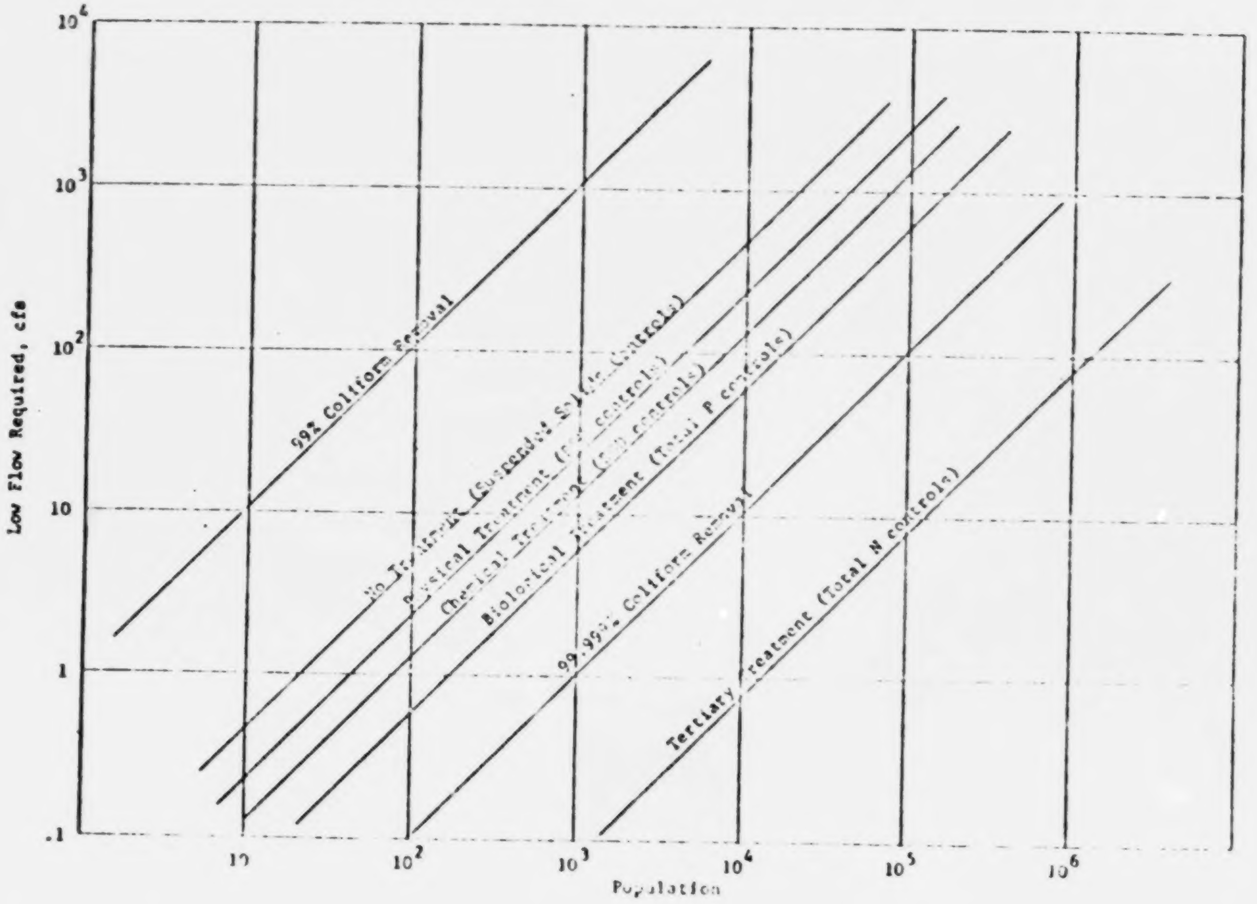


FIGURE 8: Level 1 dissolved oxygen model

From: Bishop, Robert A. and Scott, James W., 1973. "The Determination and Establishment of Minimum Streamflows in Washington State," Washington State Department of Ecology, Olympia, Washington, Draft Report No. 73-033, 81 pp.

A = cross-sectional area (average) of reach under study

Q = stream discharge

L = waste loading in mg/L

x = distance (Thomman, 1972).

K_d is the deoxygenation coefficient for carbonaceous oxygen demanding wastes. It is found by incubating samples of diluted waste material at 20°C for 20 days. The amount of carbonaceous BOD remaining in the samples is determined each day and plotted against time on log-log paper. The slope of the line determines K_{d20}, which is the decay coefficient at 20°C. Where the actual modelled water temperature differs from 20°C, the decay coefficient is modified by equation 12 to determine the decay rate at temperature T.

$$K_{dT} = K_{d20}\,(1.047)^{(T-20)} \qquad (12)$$

The only really weak feature of the Streeter-Phelps model is the reaeration coefficient. Decay coefficients may be determined under precise laboratory conditions, but the mechanisms involved in physical reaeration have largely been determined from empirical observation. Early theories of the reaeration process assumed that reaeration was accomplished by the rotation of thin, supersaturated film of water from the stream surface to the bottom. During each cycle, oxygen diffused away from the zone of supersaturation into the relatively depleted water at depth. Therefore, the rate of reaeration was a function of the mix interval, which is determined by depth and velocity, and the diffusivity, which is a function of water temperature and the oxygen deficit in surrounding water.

O'Conner's (1958) formulation for the reaeration coefficient is :

$$K_{a20} = \frac{(D\ u)^{1/2}}{H^{3/2}} \tag{13}$$

where,

D is the diffusivity of oxygen at 20°C

u is the average stream velocity

H is the average stream depth (O'Conner and Dobbins, 1958).

This formulation was determined primarily from empirical observation. While figures given may be reasonably accurate, large variations in depth, velocity, and turbulence within even a short reach can cause major inaccuracies in the reaeration coefficient.

Alonso, et. al. (1973) have formulated an expression for the reaeration coefficient which includes terms for turbulence, and suspended sediment, which can also affect the rate of reaeration. Their formulation is given in equation 14.

$$K_{a20} = \frac{6.19 \times 10^{-4}\ V_{*b}}{1 + 9.6 \times 10^{-8}\ C^{1.90}\ r} \tag{14}$$

where

V_{*b} = bank shear velocity = $(gds)^{1/2}$
g = accleration due to gravity
d = depth
s = slope

C = average suspended sediment concentration

r = hydraulic radius

The researchers found that this equation replicated the findings of experiments using a flume, but cautioned that the method may work only in streams where the ratio of bank shear velocity to hydraulic radius is constant, and there is no change in the sediment concentration. This method, while considerably more sophisticated than the O'Conner and Dobbins coefficient, still does not solve the problem of in-stream variation. Determining section size, and grouping sections with similar hydrologic characteristics remains the most serious problem in determining the reaeration coefficient.

All reaeration coefficients must be corrected for temperature by the use of equation 15.

$$K_{aT} = K_{a20} \times 1.024^{(T - 20)} \qquad (15)$$

The determination of photosynthesis and respiration by plants is often a difficult and time consuming problem. It is compounded if enrichment is occurring, causing great fluctuations in the algal flora of the river. However, since animals requiring a certain oxygen concentration to survive may be limited by relatively short periods of low oxygen concentrations, the minimum concentration is usually far more important than the average. The minimum occurs generally around dawn, after a full night of respiration and no photosynthesis.

Dissolved oxygen modelling may be quite simple, as was demonstrated in figure 9. It may also be extremely difficult. The model presented here is actually quite simplified compared to many which have been developed. The accuracy and precision of the results of the model are largely determined by the accuracy and precision of the inputs. Some of these inputs are very difficult to measure accurately, and the number of inputs needed may often seem unreasonable. However, the advantage of modelling the effects of reduced discharges and increased waste loading certainly outweighs any empirical approach because of its predictive ability.

Methods relating streamflow to infiltration and evapotranspiration

No simple or entirely satisfactory method has yet been devised for the determination of discharge requirements to supply evapotranspiration. The current concept of discharge requirements for riparian vegetation is that the shallow water table is recharged by high spring runoff.

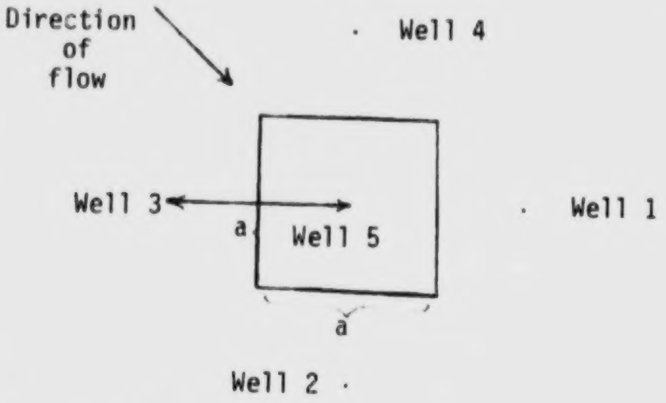
Two separate mechanisms are involved in this recharge process. Overbank flooding is an important means of adding water to bank storage through vertical accretion. Recharge is also accomplished by seepage of water out of the stream channel. During floods, the stream bottom becomes mobilized, allowing a faster rate of infiltration into the groundwater table. As the flood stage subsides, fines are deposited on the bottom, decreasing the permeability of the streambed. Because of this sealing phenomenon, most of the recharge of shallow ground water areas occurs during periods of increased flow. While some recharge occurs during non-flood flows, it may not be sufficient to provide the storage requirements of the riparian vegetation.

Thus, there are two unknowns confronting researchers of this problem. First, the rate of evapotranspiration must be determined over the growing season to establish the demand. Secondly, the amount of storage required, and the discharge which will give that storage must be determined.

Burkham (1970) and Coffin (1968) both develop expressions for relating some relationship of channel geometry and discharge to the rate of infiltration. Coffin relates channel width to vertical permeability, while Burkham uses equations which combine one or more relationships between discharge and stream geometry, and assumed relationships between geometry and infiltration.

The problem of estimating the rate of evapotranspiration has been studied by Weeks and Sorey (1973), who used finite difference equations in conjunction with an array of observation wells. The well array is shown in Figure 9 below. This method requires a continuous record of water level fluctuations in the observation wells.

Figure 9: Observation well array used in the estimation of evapotranspiration. From: Weeks, E.P. and Sorey, M.L. 1973. Use of Finite Difference Arrays of Observation Wells to Estimate Evapotranspiration from Groundwater in the Arkansas River Valley, Colorado. U.S. Geological Survey Water Supply Paper # 2029-C.



Several assumptions must be made in the use of this method:

1. The thickness of the aquifer is uniform.
2. Transmissivity and specific yield are constant.
3. The bedrock surface is horizontal.
4. Changes in water level are small compared to aquifer thickness.
5. Vertical flow accretions are negligible.
6. Horizontal accretion is uniformly distributed.

The amount of storage within the aquifer block is given by the relationship between the specific yield, or the volume of water released per volume of aquifer, and the thickness of the aquifer. The change in storage is determined by the rate of inflow, both through seepage and vertical accretion, and outflow, via throughflow and evapotranspiration. Thus, the mass balance equation for changes in storage is:

$$S = Q_i + Q_v - Q_o - Q_{et}$$

where,

S = change in storage

Q_i = subsurface inflow

Q_v = vertical accretion

Q_o = subsurface outflow

Q_{et} = evapotranspiration

Therefore, the volume rate of outflow due to evapotranspiration can be estimated by determing the change in storage, inflow and outflow. This relationship may be written as

$$Q_{et} = Q_i + Q_v - Q_o - S$$

Given the aquifer block of area a^2, the inflow into the block is determined by the relationship

$$Q_i = T (h_3 + h_4 - 2h_5)$$

where,

T = transmissivity of the aquifer

h_3 = water level altitude in well 3. Other h terms similarly defined.

Vertical accretion into the aquifer block is given by the rate of vertical movement of water to the aquifier, multiplied by the area of the aquifer block, or

$$Q_v = a^2 W$$

where,

a^2 = area of the aquifer block

W = vertical velocity of percolating water.

Outflow via seepage is determined from water levels in the same manner as was inflow, such that,

$$Q_o = T\ (2h_5 - h_1 - h_2)$$

Changes in storage within the block are equal to $a^2S\ (\ h_5/t)$, where S is the storage coefficient and t is the time interval. The terms a and h have been previously defined.

The estimated rate of evapotranspiration can be given by the formula:

$$Q_{et} = T\ (h_1 + h_2 + h_3 + h_4 - 4h_5) + a^2\ (W - S(\ h_5/t))$$

The authors warn that the above relationship holds only if the actual field conditions resemble those described under the assumptions. For the nonhomogeneous aquifer, the problem is complicated by variations in transmissivity. For example, if the transmissivity from well 5 to well 1 is less than that from well 3 to well 5, a greater decline in head will be necessary from well 5 to well 1 to maintain a given rate of flow. It seems likely that large variations in extent and type of vegetation within the aquifer block could also complicate the results.

Weeks and Sorey have developed a more sophisticated model, following the same general mass balance equation, which treats variability in transmissivity. The reader is referred to the original manuscript for further treatment of the subject. Winter water level data were analyzed to determine the accuracy of the inputs while evapotranspiration was zero. Using the above equation, the correlation between water-table curvature ($h_1 + h_2$

$+ h_3 + h_4 - 4h_5$) and changes in water table level for data from one site was so poor that there was nearly a 5% probability that it could have occurred by chance alone.

This type of methodology could be used to determine the amount of storage required to supply riparian vegetation with needed water. Burkham (1970) and Coffin (1968) both state that infiltration into the bed and banks of a stream is a non-linear function of the discharge. The change in discharge which becomes apparent as one moves downstream is due to water loss into the bed and banks. A possible method for determining the relationship between discharge and infiltration is here suggested.

Two staff gages could be established at points along the river where both can be seen easily. The interval between gages should be fairly short (100 - 200 m). A rating curve of discharge vs. gage height is established for both staff gages, so that the discharge at both can be determined at the same time. The difference between the discharge at the upstream gage and the discharge at the downstream gage is the seepage loss. This seepage loss could then be plotted against discharge at the upstream gage to determine the relationship between discharge and infiltration. It is likely that several of these sites would be needed for each river study.

By making two plots, one during the summer and one during the winter, it would be possible to estimate the effect of evapotranspiration on the seepage rate. This seepage rate could then be located on the infiltration vs. discharge curve to determine the discharge required for evapotranspiration.

Discussion of methods

The detailed data methods of California, Oregon, and Washington are equivalent in terms of information produced. Both California and Oregon use a transect method in which flow recommendations are made from discharges giving a certain usable portion of the transect for a particular set of criteria. Under these methods, there is a high probability that considerable variation may exist among the transects which could be due to chance alone. Therefore, site randomization and a fairly large number of transects are needed. The California method generally uses 40 transects per river system. The Oregon method utilizes transects in selected areas, depending on the function (passage, spawning, etc.) being measured. It would seem that the number of transects used, and their locations could result in significant variation.

The Washington method for determining spawning flows measures suitable conditions over an area, with three sites selected and four transects measured per site. By using entire areas and a set of closely spaced transects, variations within the area may be determined more readily than with other methods. A total of twelve transects would be measured per river system. In addition, the Wahington method uses planimetric maps which can aid significantly in the presentation and discussion of recommended discharges.

The validity of the Montana method has been demonstrated often in trout streams in a number of states. However, streams such as these typically exhibit a more stable daily and seasonal flow pattern than do many of the so-called "plains streams." Since the Montana method is based on a percentage of the mean annual flow, it is likely to be more valid when applied to streams in which the flow variation has a more normal distribution. Streams which demonstrate a wide flow variability are often not normally distributed, but have skewed flow distribution patterns. It would probably be possible to follow the same procedure used in establishing the original Montana method in assessing the discharge required for in-stream uses, but generalization as a percentage of the mean annual flow might not be possible. The Montana method has the unique property of expediency, and can be applied in a very short time to any stream with discharge records. It can also be applied on rivers too deep for wading, or which do not have cableways over the transect areas. This is a serious deficiency in many of the detailed data methods.

The method devised by the Bureau of Sport Fisheries and Wildlife is also expedient and inexpensive. This method contains many of the advantages of the Montana method, but allows for flow variation which mimics the flow distribution pattern of the river under study. The major disadvantage of this method is that flow adjustments over the 10-percentile baseline flow may be taken as subjective judgements on the part of the biologist. This factor might make the method difficult to defend where competition for a short supply of water was intense.

Table 10 summarizes the main characteristics of five currently used minimum flow methodologies. A great deal of research has been undertaken in the development of methodologies dealing with spawning requirements. However, only a limited number of states or agencies have attempted to define requirements for rearing flows. None of the methods reviewed is completely adequate for the determination of minimum rearing flows. The Montana method is probably the best in this regard, but even this method is largely subjective, and rearing flows would probably be difficult to defend. In the cases of the detailed data methods, the biological criteria used in the recommendation of rearing discharges are often vague and very broadly defined. For example, some of the guidelines used by the California method define suitable riffle depths as being in the range of 2.5 to 91 cm. For many riffle areas, this range would encompass the entire riffle, regardless of the discharge. Therefore, it would be extremely difficult to predict discharge related changes in insect productivity by the guideline alone.

A common criticism of all the methodologies in current use is that they often tend to recommend discharges which exceed the natural discharge of the river during a particular time (Milhous, 1973). This criticism may be justified if the recommended flow is higher than the average or modal flow for the same time period. However, it is dangerous to assume that because the discharge is periodically lower than the recommended discharge, that something is wrong with the methodology. On the contrary, stream communities are accustomed to short periods of low flow, and can survive such periods by retreating to pools or other "in-stream havens."

TABLE 10: Characteristics of various minimum flow recommendation methodologies.

Characteristic	California	Oregon	Washington	Montana	BSFW
Applicable to large streams				X	X
Applicable to small streams	X	X	X	X	
Uses field measurement and biological criteria	X	X	X		
Uses professional judgement				X	X
Discharge records required				X	X
Considerations					
Spawning	X	X	X	X	X
Migration		X		X	X
Insect productivity	X	X		X	
Suitable habitat	X	X	X	X	X
Water quality					
Dissolved oxygen			X		
Temperature					
Sediment transport					
Toxic materials					
Riparian vegetation					
Recreation			X	X	
Personnel required	Aquatic biologists, field assistants	Aquatic biologists, field assistants	Aquatic biologists, field assistants (sanitary engineer, computer programmer)*	Office personnel	Office personnel
Estimated cost/river ($)**	6-10,000	1000-6000	1000-25,000	>100	>100

* Depending on the sophistication of the method used in water quality studies

** Estimated man-days @ $30/ man-day, assuming five different discharges measured. Does not include capital equipment.

However, a continuous discharge at these low rates would undoubtedly result in major modifications in the community structure.

None of the methodologies in current use considers the effects of reduced discharge on summer stream temperatures, winter conditions, or riparian vegetation. It is not now apparent whether these values will over-ride (require additional discharge) the flow recommendations based on generalized fishery requirements. It is not likely that reduced streamflow will affect maximum temperatures before some in-stream change occurs, but there is no way,short of modelling the temperature, to be certain. Further research in these areas is required before the critical consideration for a particular time period can be identified. Perhaps the most critical over-riding consideration is the discharge-sediment equilibrium between the stream and its drainage basin. It would be entirely possible that the discharge which is considered adequate from a fisheries viewpoint could still result in the aggradation of the stream, with the consequent modification of the community.

A PROPOSED METHODOLOGY FOR RECOMMENDING MINIMUM STREAMFLOWS IN THE NORTHERN GREAT PLAINS

Methodologies used in the determination of minimum streamflow requirements must meet two general criteria: (1) they must meet the biological requirements for all stream associated organisms; and (2) they must not be overly expensive and time consuming. Therefore, a compromise must be struck between absolute reliability and practicality. However, reliability must be given a high premium.

The methodology proposed may be designated the "indicator species-over-riding consideration" method. The premise for this method is that, if environmental conditions are not unfavorable for the species with the narrowest ranges of discharge requirements, they will likely be suitable for all other organisms as well. An indicator species is defined as the species which demonstrates the narrowest range of tolerances or requirements for any particular biological function. Therefore, the same indicator species is not used for every phase of the life history. This method recognizes three basic biological phases in the life histories of the fish: migration, spawning, and rearing. Rearing is further subdivided into quantitative (production) and quality (balance) terms.

The indicator species for migration and spawning requirements in large rivers of the Northern Great Plains is the paddlefish (Polyodon spathula). This species is likely to have the most restrictive migration requirements because it is a very large, deep-bodied fish, and obviously has the greatest clearance requirements over shallow sand bars. The paddlefish also requires a substantial rise in stage before migration is initiated. Stockard (1907) indicates that the paddlefish usually has no trouble spawning if it can successfully migrate. Therefore, it is not necessary to measure the spawning sites, or even to know where they are. Measurement is expedited by locating the bars most likely to impede passage. For rivers which do not contain spawning paddlefish, the migration and spawning indicator species suggested is the sauger (Stizostedion canadense). This species is chosen over the walleye because it spawns earlier in the season, and is also more widely distributed. Since the sauger is frequently found in rivers containing the paddlefish, but migrates earlier in the year, the migration requirement for paddlefish should be initiated during the period of migration of the sauger. This discharge should be maintained for at least three months from the initiation of sauger spawning, to insure the proper development of northern pike eggs in flooded shallows. The clearance requirements for these species are not yet known, and should be measured or defined before these species can be used to recommend migration and spawning discharges.

The methodology suggested for the recommendation of migration and spawning discharges is the usable width method as developed by the Oregon Fish Commission. Gravel and sand bars which are most likely to impede the upstream migration of the indicator species must be located, and a transect measured across the shallowest course from one side of the river to the other.

At each of several discharges, the total width and the longest usable portion of the transect meeting minimum depth and maximum velocity criteria are measured. The total usable width and the longest continuous portion of each transect are each plotted against discharge. Because the paddlefish requires a rise in stage of at least a meter, it is recommended that the discharge which meets clearance criteria over 50% of the total transect width and a continuous portion equalling at least 30% of the total transect width be used as the minimum migration requirement for the paddlefish. These percentages may be subject to revision pending research on migration stimuli and passage requirements.

For lower reaches of larger rivers, where the paddlefish normally spawns, the migration flow recommendation for the paddlefish may also be recommended as the spawning flow. Since paddlefish spawning is determined primarily by migration success, it is reasoned that adequate migrational discharges will also be adequate for spawning. Thus, for these rivers, the migration and spawning flow may be determined by the migration requirements of the paddlefish, and extended over the three month period suggested.

For reaches of streams which do not have spawning paddlefish, the indicator for spawning is the sauger. The criteria for sauger spawning may be inferred from the text, but should probably be measured. The criteria suggested are those areas which provide the greatest egg survival. These areas are generally over clean swept gravel bottoms, where the depth ranges between 1.0 and 1.5 meters and the velocity ranges between 0.3 and 0.75 m/sec.

The methodology suggested for the analysis of spawning site suitability is exactly the same as the Washington method. Six likely spawning sites are located which are representative of most of the spawning sites in the river. Four transects are established across each site, with cross-sections about 10 meters apart. The depth and velocity are measured at 0.5 meter intervals across each transect. Velocity should be measured at 0.6 of the total depth in water less than 0.5 meter deep, and averaged from measurements taken at 0.2 and 0.8 ot total depth in water deeper than 0.5 meters. Cross sectional depth and velocity data for at least five different discharges are then plotted on separate planimetric maps of each study reach. Isolines of equal depth and velocity are drawn on the maps, and a composite map showing areas meeting criteria for depth and velocity is constructed for each discharge. These areas are then determined by planimeter or planimetric graph paper, and plotted against discharge. The resulting curve gives a figure for the optimum spawning discharge. The minimum sustaining discharge is defined as 75% of the optimum. This recommended spawning discharge should also be extended for at least three months, beginning with initiation of sauger spawning, to insure the successful spawning of later spawning species.

Successful rearing of stream fishes requires that the food base is adequate, that food is consistently replenished through drift into pool areas, and that microhabitat and water quality requirements of the species inhabiting the pool areas are met. Because riffle areas are more seriously affected by reduced discharges, it is reasoned that the maintenance of suitable riffle conditions will result in suitable pool conditions as well. For this reason, a swift water species, the stonecat (Notorus flavus), is chosen as the rearing indicator species.

Analysis of habitat for this species requires the use of criteria as suggested in the text. However, actual habitat preferences for the stonecat, including young of the year, should be measured. Analysis of areas of suitable habitat is patterned after the Washington method as discussed under spawning. Six to nine areas which are likely habitat for the proper indicator species are selected, and four transects established over the area. The same procedure is followed in the construction of composite maps to determine the area of optimum habitat at five different discharges. The minimum rearing habitat is defined as 75% of the optimum habitat, as described under the section on spawning.

Criteria for riffle productivity are suggested in the text as those areas which have rubble bottoms (bed materials greater than 6 cm in diameter), with the depth range for optimum production between 8 and 23 cm. The velocity criterion for optimum productivity is recommended to be the range of 30 to 46 cm/sec. Analysis of riffle production is on the basis of the optimum area available at a given discharge, and is determined according to the graphical method as described above. Six to nine areas of riffle are selected according to bottom type, and four cross-sections are established at equal intervals for the length of the riffle. Depth and velocity measurements are then made at 0.5 meter intervals (velocity measured at 0.6 total depth). This data is then plotted on separate planimetric maps, as above, for at least five separate discharges. A composite map detailing the area of optimum productivity for each discharge is then compiled and analyzed planimetrically. The minimum productivity habitat is defined as 75% of the optimum as determined by the discharge-optimum area curve.

The minimum discharge for riffle productivity is then compared with the minimum discharge recommendation for the rearing habitat indicator species. Whichever discharge is greater is defined as the minimum recommended discharge. This is termed an over-riding consideration. Other over-riding considerations have been discussed in the text. Each of these considerations deserve further study to determine which, if any, require greater discharges than those required by the indicator species for a particular time period. It is not likely that temperature will be an over-riding consideration as other quantifiable changes will occur before temperatures become limiting. However, dissolved oxygen may become an over-riding consideration as regional populations grow, and the waste assimilation capacity of the dewatered rivers is taxed in increasing amounts. The flow requirements for bank recharge and the maintenance of riparian vegetation could well exceed those for migration and spawning. However, it is not clear at this time, which function will be over-riding. Further research is definitely needed in the determination of discharge requirements of riparian vegetation. Additional information is also required concerning the relationship between discharge and anchor ice formation.

The ultimate over-riding consideration is the equilibrium condition between sedimentation and discharge. Unfortunately, a good method has not been developed to predict the discharge requirements for the removal of sediment from a drainage. It is recommended that any study to recommend a minimum discharge should include provisions for the establishment of permanent vigil network sites.

A vigil network site includes several surveyed transects, from which the relative elevation of the stream bed, the width of the channel, and the shape of the channel may be monitored. Comparison of surveys with baseline data can indicate the equilibrium condition of the channel with its drainage, and can also indicate rates of degradation, aggradation, or stream width changes.

APPENDIX I

STREAMFLOW AND THE BENTHIC COMMUNITY

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A. Water Velocity

Bottom dwelling invertebrates inhabit what is known as the boundary layer of water at the bottom of the stream. Velocity decreases rapidly near the bottom of the stream, but the rate of decrease depends on the roughness of the bottom. Resistance to flow is greater along a rubble bottom than it is along a bottom of sand. Adjacent to the bottom, the velocity is theoretically zero. As with the rate of decrease, the thickness of this boundary layer is dependent on the size of the bottom materials. Because flow in natural rivers is turbulent, the resistance produced by the boundary surface is not a function of the Reynolds number (a measurement to determine whether flow is turbulent or laminar), but depends on the ratio of depth to size of the roughness elements. Therefore, resistance to flow provided by the boundary layer is greater in water which is shallow with respect to the size of the bottom materials (Leopold, Wolman, and Miller, 1964). Thus, current velocity which is important to bottom organisms is determined by the size of the bottom materials and depth of water. Conversely, on the larger hydrologic scale, it is current velocity and depth which determine the size of the bottom materials in any given place. These variables are inextricably tied, and are a source of considerable disagreement as to which is the most important in determining invertebrate distribution.

For some species, current velocity appears to be the most important variable in a stream's hydraulic geometry. Sprules (1947) felt that within the constraints set by temperature, the distribution of species was affected most by current velocity and bottom type. Many species are limited by some inherent demand for current, either as a source of oxygen renewal, or food supply. The respiratory physiology of some invertebrates requires a current. Nymphs adapted to swift water are forced to swim and may die under conditions of reduced water velocity. Stoneflies (Plecoptera), for example, do not have moveable gills, and rely on water movement for oxygen renewal. When placed in still water, many species demonstrate stress reactions by moving their bodies up and down in the water as if they were doing "push-ups."

Wu (1931) states that Simulium larvae have a definite requirement for current, and a high dissolved oxygen content in the water is not the determining factor for their presence or absence. Where food was plentiful, Simulium became established in velocities never lower than 17.7 cm/sec (.58 fps), with the majority of the colonies in much faster water. Wu found that in some cases there was evidence that the accumulation of sediments was a determining factor in the suitability of a certain current velocity. He also determined that the minimum current rate for Simulium was lower in streams with a high food source, than in streams with a low food source. Wu states that for the Simulium, the requirement for a current goes beyond respiration and food acquisition:

> "The important factor of oxygen supply does have immediate effects on the organisms and it seems to explain the response of the larvae on the supposition that the weaker current cannot meet their high oxygen requirement. But when the situation is examined closely, such an explanation cannot be applied. The dissolved oxygen content of the surface water is high, and furthermore, the water in contact with the body surface and anal gills is changed even with a very slow current. Under such conditions it seems difficult to suppose that the larvae are unable to effect adequate exchange of gases. The very fact that not all the larvae left the new environment simultaneously is a proof that the cause of their restlessness is not suffocation.....This behavior appears, therefore, to be a mere response to the change in pressure."

Edington (1968) determined that for net spinning Trichoptera (caddis fly larvae) of the families Philopotamidae, Hydropsychidae, and Polycentropidae, the size and shape of the net was a limiting factor in the preference of current velocity of each species. The nets of species of Hydropsyche are small, rigid, and highly streamlined. Because of the small opening in the net, a large volume of water must be filtered to obtain food. Hydropsyche instabilis cannot survive low oxygen concentrations unless the water is moving, and shows a velocity preference between 15 and 100 cm/sec (0.49 - 3.28 ft/sec). Polycentropus flavomaculatus, on the other hand, shows a velocity preference for velocities between 0 and 20 cm/sec (0 -.65 ft/sec). This species builds a large, floppy net which can filter a large area of water, but which is destroyed by fast water. Plectrocnemia conspersa builds a net which collapses in a current less than 13 cm/sec but which is burst by a current faster than 17 cm/sec (.43 - .56 ft/sec), which must restrict its range severely (Macan, 1963).

Sprules (1947) found that the Simuliidae demonstrated an inherent current demand, described by Wu (1931). The Ephemeroptera (mayflies), Trichoptera (caddis flies), and Chironomidae (non-biting midges) were not so directly limited by current since there were different species associated with different currents. Macan (1963) goes on to explain that while some invertebrates are certainly adapted to life in a fast current, such as the Simuliidae, Rhithrogena (a mayfly with an extremely flattened body), or many of the Plecoptera (which have flattened bodies and immoveable gills), most animals which dwell in running water have adaptations in behavior, not of structure, which allow them to avoid the effects of the current. That reduced current limits the abundance and diversity of swift water invertebrates has been demonstrated often. However, the reduction in velocity may not directly cause death, or desertion of habitat, but may encourage sedimentation which selects against these behavioral adaptations (such as living in crevises between stones).

Further evidence of the importance of current velocity in the distribution of benthic invertebrates is given in an excellent study by Needham and Usinger (1956). They found striking correlations between insect distribution and depth and velocity. They noted little correlation between distribution and substrate size, but cautioned that the riffle they were sampling was extremely uniform. The greatest numbers of Ephemeroptera were found in velocities of 40 to 85 cm/sec (1.2 to 2.6 ft/sec), with depths less than 30 cm. Trichoptera were most abundant in velocities of about 1 m/sec (about 3.0 ft/sec) and depths of about 30 cm. Simulium occurred in fast water with velocities averaging about 1 m/sec.

Giger (1973) has carefully summarized the results of three studies which demonstrate the relationship between water velocity and numbers of organisms. Hooper (1973) presents data from an unpublished report for the same relationship. Table 1 (pg. 26) is a comparison of the data from five separate studies which relate water velocity to abundance of stream organisms. Since different sample sizes were taken, numerical comparison is possible only within individual studies. However, the results are quite consistent, given the variability of even a single uniform riffle as demonstrated by Needham and Usinger. Some variation is undoubtedly caused by velocity measurements being made at different depths in the water column. The depth at which velocities are measured should be standardized (i.e. as .6 of total depth, or 3 cm from the bottom, etc.) so that all researchers are measuring the same thing.

However, from evidence presented during this discussion it is probable that the velocity actually encountered by most stream invertebrates is close to zero. This is particularly true for invertebrates which have behavioral adaptations, rather than physiological ones, for living in areas of fast water. Therefore, the actual velocity encountered by each organism in a riffle may be academic, and has actually never been measured. The important concept, and one which is quite quantifiable, is the maintenance of the habitat type, or substrate. A primary consideration then, should be velocity as it affects the transport of sediment across the riffle. This idea will be developed in the discussion of the influence of substrate on the distribution of invertebrates.

In a list of guidelines for biological criteria for the recommendation of rearing flows, the Oregon State Game Commission recommends riffle velocities of 30 to 45 cm/sec (1.0 to 1.5 ft/sec) (Thompson, 1972). Guidelines for California define food producing areas as those where the velocity near the bottom is 15 to 45 cm/sec. The depth at which the velocity is measured is not specified, and has been shown to be quite important. Giger (1973) states that velocities near 15 cm/sec are too marginal and that an ideal range would be from about 30 to 60 cm/sec. Hooper (1973) recommends that the California guidelines might be refined to consider velocities of 45 to 105 cm/sec as optimum for food production. Hooper further recommends that emphasis should be placed on determining changes in velocity over riffle areas outside the main channel, as these are the most productive.

B. Depth

As was mentioned previously, the resistance to flow is greater when the size of the bottom materials is large compared to the depth of the water. Increased depth over a riffle area, combined with high velocity, results in an increase in the tractive force, and therefore, the ability to scour.

In the study by Needham and Usinger (1956), the greatest numbers of insects occurred in riffle areas from 8 to 22.5 cm (3 to 9 inches) in depth, with numbers increasing up to 22.5 cm and dropping off at greater depths.

Kennedey (1967) found the majority of bottom organisms in 8 to 15 cm of water. Depth criteria used in California ranges from 2.5 cm to about 1 meter (1 inch to 3 feet) over riffle areas (Hooper, 1973). These criteria are obviously quite generous and should be refined. Criteria for depth used by the Oregon State Game Commission is defined as "adequate" depth over riffles (Thompson, 1972). This criterion is even more generous and should be quantified. A more restrictive range of optimum depths for food production in riffles might be defined as 8 to 23 cm (3 inches to about 10 inches).

C. Stream Width

Intuitively, it would seem that a wide stream riffle would produce greater amounts of stream invertebrates simply because there is more area for production. However, productivity per unit area actually increases in some smaller streams (Giger, 1973).

In terms of total production of food organisms, a wider section usually will produce more organisms. One possible explanation for the greater unit production by small streams stems from the distribution of allochthonous material. On a small stream, bank vegetation is relatively close to the center of the stream, as compared to vegetation along a wide stream. Therefore, there would be relatively greater amounts of allochthonous material per unit width in a small stream than in a large one.

Another factor may be strictly hydrologic in nature. Portions of wide streams may be too deep and too fast, or may be braided channels with large islands in the center of the channel. Either situation may be unusable by the aquatic invertebrates. Thus, a small stream is likely to have a higher percentage of "usuable bottom" across its entire width than a wide stream. In general, overall production of benthic invertebrates is reduced in accordance to reductions in wetted surface area, although this relationship is not linear (Giger, 1973).

D. Bottom Type

The bottom type or substrate is a reflection of the hydrological equilibrium conditions of a given reach. Subjectively, it is easy to characterize a stream section with a large rubble bottom as being very swift and fairly deep, whereas a section with a mud bottom is likely to be very deep and sluggish. These interrelationships of hydrologic variables make it extremely difficult to determine exactly which variable is the most important in the distribution of invertebrates on the bottom.

Sprules (1947) maintains that the diversity of insects in any area is related to the number of different microhabitats present in that area. Large bottom materials provide the greatest amount of surface area exposed to the water, and in conjunction with velocity and turbulence, the greatest variety of microhabitats. However, there appears to be an upper limit to this phenomenon. Kennedy (1967) determined that most organisms were found on or under rocks which were between 6 and 18 cm in diameter (about 2½ to 7 inches).

Unfortunately, substrate size has not been standardized by aquatic biologists in the same terms as those used by hydrologists and engineers. Thus, descriptive terms such as rubble may be quite confusing unless actual measurements of bottom materials have been made. The Wentworth Grade Scale is presented in Table 3 (pg. 30), and can be used to classify actual particle size ranges by name. This grade scale has many more divisions than are generally used in aquatic biology. The classification of rubble in many studies, corresponds to the Wentworth classification of small to very large pebble. The term gravel is commonly used by biologists, and corresponds to the granule on the Wentworth scale. The terms sand and silt are essentially the same for both systems. What is referred to as a mud substrate (or often as muck) by biological reports, generally corresponds to the Wentworth classification of clay.

Under natural stream conditions, medium sized rubble (i.e. medium pebbles) is considered the most productive substrate type. Productivity drops off with decreasing substrate size down to a sand substrate, and then rises again in mud-detritus substrates. Wene and Wickliff (1940) found that placing a wire basket filled with small pebbles into a sand bottomed pool increased insect productivity three-fold. Baskets containing large pebbles increased insect production five-fold. The greatest increases were shown in the orders Ephemeroptera, Diptera, and Coleoptera, indicating species without inherent current demands.

Sprules found that rubble in moderately fast water not only had the most insect fauna, but that the distribution of all groups of insects was the most equitable over a rubble bottom. The Chironomidae formed the most abundant element (38.2% by number), followed by Ephemeroptera (35.5%) and Simuliidae (10.8%). Plecoptera and Trichoptera followed in descending order. Over a gravel bottom, the Chironomidae were again the most abundant group (67.6%) followed by Simuliidae (21.4%) and Ephemeroptera, Plecoptera, and Trichoptera in decreasing numbers. The insect fauna over a muck bottom was the next most productive bottom type, with Chironomidae clearly predominant (74.8%) with Ephemeroptera a distant second (20.3%). Simuliidae and Plecoptera were not represented at all over the muck bottom. A bottom of pure sand was the least productive, with the fauna almost entirely composed of Chironomidae (83.9%).

Scott (1966) points out that the size and distance apart of stones on a river bed may be important in determining population density of the invertebrate fauna. Some species or species groups appear to show an increase in density when the proportion of the total stream bed covered by stones increases. Other elements of the fauna did not show such a response until forced by some other environmental parameter. For example, some species of Trichoptera moved into more protected microhabitats only under conditions of increased current velocity.

For some species, the size of the interstices between the bottom materials does appear to be important. This is particularly true for those species showing behavioral adaptations for life in running water. Percival and Whitehead (1929) investigated the distribution of invertebrates on substrates which differed primarily in the size of particles and the degree of cementation by sand, silt, or vegetation on and between the individual bottom materials. Table 2 (pg. 29) is a simplified summary of some of their data, showing the relationship of the distribution of certain genera and the size and degree of cementation of the bottom materials. The relationship shown by Percival and Whitehead is that most of the genera studied preferred areas where there was little cementation by silt between bottom particles. Where the bottom itself was highly cemented, the organisms took shelter in and beneath filamentous algae (Cladophora) or loose moss, such as growths of Fontinalis. However, some species did choose open water areas where there was little protection from the current. Among these were Agapetus, Glossosoma, and Psychomyia, all caddis larvae, and the mollusc, Ancylus. Macan (1963) notes that Ancylus is one of the few genera which habitually sit on tops of stones in torrential currents, and hence must be adapted to resist a swift current. Glossosoma nearly always selects fast water over a clean swept bottom, possibly because it does not like silt in its food (Macan, 1963). Of particular interest is the poor swimming Gammarus. This is an important food source for many fish species, and it seems to be confined primarily to areas which offer good protection from the current. Thus, it is easy to see that while such animals as Rhithrogena, Ancylus, and Gammarus may all be found in swift currents, their individual substrate needs are quite different.

Because substrate type is both a product and a local modifier of hydrologic conditions, Thorup (1966) states that substrate type is a better characteristic than stream zonation to use as a basis for a system of biocoenoses, even though variations occur in the faunal composition on certain substrates. However, because of these variations substrate alone is not sufficient for the construction of a system of biotopes, and depth and velocity must be considered.

E. Food Distribution

The distribution of invertebrate food sources is similar to the distribution of substrate type in terms of hydrologic variables. In swift water, all but the coarsest materials are swept away by the current, while in regions of reduced velocity, the finer particles settle to the bottom. Periphytic algae are responsible for most of the primary production within lotic habitats, and has been shown to grow best in areas of moderately fast water (Cummins, 1966). The realization that primary production alone is not sufficient to support the total stream biota emphasizes the importance of allochthonous material. The distribution of these food materials in streams is such that the food source in riffle areas is primarily algae, while in depositional areas the food source is primarily detritus. However, Egglishaw (1964) reports considerable amounts of detritus settling out in riffles as well.

The distribution of bottom fauna may be highly affected by the distribution of their foods. Cushing (1963) demonstrated that the distribution of filter feeding insects is directly related to the amount of phytoplankton in the water. In a stream section below a productive lake, large amounts of plankton were available, and the proportion of filter feeding insects was greater than in an upstream reach with less phytoplankton. In the upper section, the amount of organic detritus was proportionally greater and detritus feeders were much more numerous. This relationship emphasizes the role of allochthonous material in determining distributional patterns of invertebrates.

Egglishaw (1964) attempted to sample areas of bottom differing only by the amount of plant detritus. He determined that the distributions of *Leuctra*, *Amphinemura*, *Baetis*, *Rhithrogena*, and Chironomidae were significantly correlated with the distribution of plant detritus. Other species were not correlated with plant detritus, including *Caenis*, Limnephilidae, Hydropsychidae, and *Rhyacophila*. The Trichoptera as an order showed only limited association with detritus, as many are plankton feeders. The carnivore, *Chloroperla torrentium* was randomly distributed, presumably because of its predatory habits.

The food source present in the stream is variable over a season, as well as variable in its area of production and deposition in the stream. Buscemi (1966) notes that organic drift of vegetative materials may be largely allochthonous during spring periods of runoff or fall periods of leaf fall, and largely autochthonous during summer and winter periods of low water.

The rate and areas of deposition of these materials depends on factors characterized by hydrologic conditions, such as velocity, thickness of the boundary layer, irregularities of bottom material, duration and volume of flow above normal low flow, and channel geometry; or by factors intrinsic to the organic material itself. Included in these parameters would be such things as surface area and specific gravity of individual organic particles. These factors will affect the settling velocity (the water velocity at which deposition occurs) of the organic materials. The settling velocity for sedimentary organics is likely to be less than that for sedimentary inorganics but the difference in settling rates for the two materials is not known (Buscemi, 1966).

Scott (1966) suggests that the optimum habitat for some filter feeding Trichoptera may partly be determined by low current velocities in the crevices between stones. These low current velocities would lead to the deposition of organic sediments, but would still be strong enough to move the material into the nets.

F. Flow Stability

Sudden fluctuations in water levels operate to disturb invertebrates in one of two mechanisms; dislodgement in the case of increased flow or desiccation and stranding in the case of suddenly decreased flow. Much has been written concerning the effects of fluctuating flows below hydroelectric dams, but little is known about the long-term effects of stabilized discharges (Giger, 1973).

Conditions of constant fluctuation in streamflow are noted by Giger as consistently resulting in the reduction of both production and standing crops of bottom fauna. Sprules (1947) noted that an intermittent flow and consequent drying of the stream bed limited the number of individuals and species present. Only the most tolerant of species are able to complete their life cycles in streams subjected to streamflow fluctuation. Sprules found that species with fixed habitats, such as certain of the Trichoptera and Simulidae, were eliminated rapidly as water receded from stream margins, while the free-roving forms, such as the Plecoptera and Ephemeroptera, were able to follow the receding water and avoided desiccation. On the other hand, species with fixed habitats were better able to withstand freshets than were the free-roving forms.

Hynes (1958) states that the number of species surviving a period of desiccation depends on the timing of the period with the life cycle of the species. Many species can avoid desiccation by hatching out after water has again begun to flow. While the nymphs and larvae are killed by long periods of drought, the eggs of most intermittent stream species can survive desiccation.

On a limited scale, Minshall and Winger (1968) found that virtually all bottom organisms were affected by a flow reduction of 62.5% below an irrigation diversion on a small stream. When streamflow was reduced there was initially a lateral migration followed by a great number of animals releasing from the substrate and becoming part of the drift (began floating in the current). Entry into the drift appeared to be an active behavioral process, initiated by changes in velocity and depth, and perhaps by reduction of living space, in reversal of the normal avoidance reaction to light.

Flow rates are also influenced by the formation of anchor ice during the winter months. Anchor ice is a slushy type of ice which forms on the bottoms of streams during cold weather. It is apparently the result of supercoooling the water, resulting in immediate freezing on the front side of rocks where the water velocity decreases to zero. Brown, Clothier, and Alvord (1953) observed the formation of anchor ice in the West Gallatin

River, Montana. They observed that anchor ice forms best in riffles during cold, clear nights. The velocity of water 2.5 cm (1 inch) from the bottom, at which anchor ice first started to form was about 40 cm/sec (1.3 ft/sec). Its occurance decreased at depths over .6 m (2 ft).

Needham and Jones (1959), observed the formation of anchor ice in a small trout stream in California. They noted that the key spot in the formation of anchor ice was the upstream point of stones where the current was split to each side and velocity was reduced nearly to zero. They noted that during the course of the winter, increasingly colder night-time temperatures were required for the formation of anchor ice. This phenomenon is possibly due to an increased snow and ice cover over the stream which prevented the heat loss needed for the formation of anchor ice. It was also noted that the upwelling of relatively warm ground water into the stream successfully prevented anchor ice formation.

The formation of anchor ice is an important ecological factor for both invertebrates and fish alike. Anchor ice forms on riffle areas at night, and then breaks loose during the daylight hours (Maciolek and Needham, 1951; Logan, 1963; Needham and Jones, 1959). During the night, the buildup of anchor ice causes water to be backed up into upstream pool areas. When the ice buildup breaks loose during the day, it is accompanied by a large surge of water and slush. This action dislodges considerable numbers of invertebrates and sets them drifting in the current. Drifting invertebrates are more subject to predation, so this daily surge of water acts to make food more available for fish. However, while some fish feed actively during the winter, such as the burbot (Chen, 1969), most do not. Reimers (1963) found that trout are not especially selective about their food during winter, and that their digestion rates slow down. Winter for fish, if not a period of fasting, is at least a period of poor assimilation of whatever is eaten. What is true for trout is especially true for warm-water species, such as the Ictaluridae (Simco and Cross, 1966) and the Centrarchidae (Hubbs and Bailey, 1938). Rapid improvement of body condition is fundamental for all fish species during spring when water temperature, metabolism, and activity increase. If, by spring, the food supply has been depleted by winter conditions, or the fish themselves weakened by the rigors of winter, spring mortality is quite likely to be high.

The consequences of decreased winter discharges are here presented as a hypothesis. Under normal conditions, large numbers of aquatic insects are involved in catastrophic drifting due to the release of anchor ice dams. Waters (1965) determined that drifting insects do not normally travel far per drift episode. Therefore, under normal conditions, areas depleted by catastrophic drift would pobably be recolonized quickly from upstream areas. However, lowered discharges would likely increase the recurrance and the severity of anchor ice formation. Conceivably, this could eventually lead to overwinter depletion of food production areas.

Therefore, it would seem that winter discharge recommendations should consider the prevention of flow-induced increases in the recurrance and severity of ice formation. This will require a greater knowledge of conditions favorable to anchor ice formation for a given set of climatic conditions.

Flow regulation and variation create an unnatural change in the hydrologic regime of a drainage. While flow fluctuations undoubtedly occur in natural conditions, actions to change the stream regimen tend to amplify the effects of fluctuation. Invertebrates living in streams are adapted to a certain amount of flow variation, but as has been seen, increases in the variation and the frequency of occurrance of the variation in flow can have serious detrimental effects.

These effects may be quantitative, in that areas subjected to numerous wide fluctuations in streamflow are less productive than areas with relatively stable flow rates. The effects may also be qualitative depending on the nature of the fluctuation. If the fluctuation appears as a sudden surge with a gradual decrease back down to "normal" discharge, the fluctuation will tend to select against the free-roaming forms, such as the Plecoptera and Ephemeroptera. If the fluctuation appears as a sudden decrease in the amount of discharge, followed by a slow increase back to "normal," the fluctuation will tend to select against forms which are relatively immobile, such as many of the Diptera and Trichoptera.

G. Water Quality Factors

Water quality can be demonstrated to have profound effects on the community structure of the aquatic ecosystem. In turn, water quality is directly related to streamflow, although certain parameters become more important at different times of the year. Reduced streamflow may have the following impacts on water quality, separately or in combination with one another:

1) Greater range of water temperatures, both diurnally and seasonally.
2) Decreased waste assimilation capacity, and lowered dissolved oxygen concentrations
3) Decreased sediment load capacity and competence.
4) Increased concentration of nutrients.
5) Increased concentration of toxic materials.

Water quality parameters are often interrelated, and frequently temperature is the controlling abiotic factor in these relationships. For example, the decomposition of oxygen demanding wastes proceeds at a faster rate in warm water than in cold, but the saturation concentration of dissolved oxygen is lower in warm water. Therefore, the oxidation of organic wastes is a greater problem in warm water than in cold, in terms of oxygen depletion. Bovee, et. al. (1973) found that organic wastes in a cold, fast stream had very little effect on the dissolved oxygen concentration of the stream. It was speculated that rearation was a minor factor, and that the temperature controlled decomposition rate was a major factor in these findings.

Temperature: In addition to the effects of temperature on other water quality parameters, temperature also exerts definite selective pressures directly on stream organisms. There are many animals and plants, both aquatic and terrestrial, whose ranges appear to be limited by temperature. Several examples of mechanisms involved in temperature limitation are reported here.

Macan (1963) determined that the distribution of Heptagenia lateralis was limited largely by the highest summer temperature of the water in which it was found. It abounded at every sampling site where the highest temperature was 18° C or less, and was scarce or absent from all others. The species cannot grow during cold weather, and Macan's suggestion is that its absence from the warmer streams was due to a rise in temperature from a level below which the nymphs cannot grow, to one above which they cannot live, in a period which was shorter than the time required for the full development of the individual. Had the species been able to emerge before the high lethal temperatures were reached, the species could probably have lived in "warmer" water. Macan goes on to state that Rhithrogena semicolorata is probably temperature-limited in the same way, but has a wider range than H. lateralis because it can grow at lower temperatures, and can tolerate a higher lethal temperature. Gaufin and Hern (1971) determined that insects with multiple-year life cycles were better adapted to ranges of temperature than were single-year species. However, there was considerable variation in tolerance even among the mutiple-year species.

Macan lists two basic mechanisms by which temperature may act as a limiting factor for stream insects. The temperature may be lethal to some organisms by being either too warm at its maximum or too cold at its minimum. There may be competition between closely related species, each of which is adapted to an optimum temperature range. The species which is better adapted for life in cold water will be able to compete more successfully with its warm water relative in the cool part of the zone of overlap of the two species. The converse is also true in the warmer part of the zone of overlap, where the warm water species will have the competitive edge.

Dissolved oxygen: Temperature exerts a direct influence on the concentration of dissolved oxygen in water, as well as the rate at which it is consumed. As the temperature increases, the dissolved oxygen saturation concentration decreases. At the same time, the metabolic rates of the animals living in the water increase. As a result, there is a greater demand for a resource which may, at times, be in short supply. Thus, those animals best adapted for life in low oxygen situations will probably survive at the expense of species not so adapted. Current-oriented aquatic invertebrates can withstand very low dissolved oxygen concentrations (some below 1 mg/L) if the current velocity remains high. However, in still water, the required dissolved oxygen concentration must be much higher. Figure 10 illustrates the relationship between dissolved oxygen and velocity requirements for selected genera of aquatic insects.

It can be seen from Figure 10 that those genera commonly thought of as being "torrential" fauna, such as Rhithrogena, Baetis, or Rhyacophila, generally have fairly high dissolved oxygen requirements in nearly still water, while slow-water species, such as Anabolia (which can create a current by squeezing water through its case) or Ephemerella, have nearly constant dissolved oxygen requirements regardless of current speed.

In cases of severe organic pollution, the dissolved oxygen concentration in a body of water may be completely depleted. This results in a decrease in the density and diversity of aquatic insects, crustacea, and molluscs, and often in increases in algae (through concentration of nutrients and lack of grazing), protozoans, and bacteria (Cairns and Dickson, 1972). Mills, Starrett, and Bellrose (1966) associated the loss of most forms of bottom life in the Illinois River with a "pollution complex" caused by severe organic pollution in conjunction with inorganic sediment. This pollution complex resulted in the formation of extensive sludge deposits in the river. The only major form of life left in the river was the sewage worm of the family Tubificidae.

Larimore, Childers, and Heckrotte (1959) examined the effects of oxygen depletion caused by drought and decomposition of leaf litter in a small midwestern stream. They found that many of the fish species could actually outlive the stream invertebrates under oxygen depleted conditions because they could swim to the surface for gulps of air. After water had again

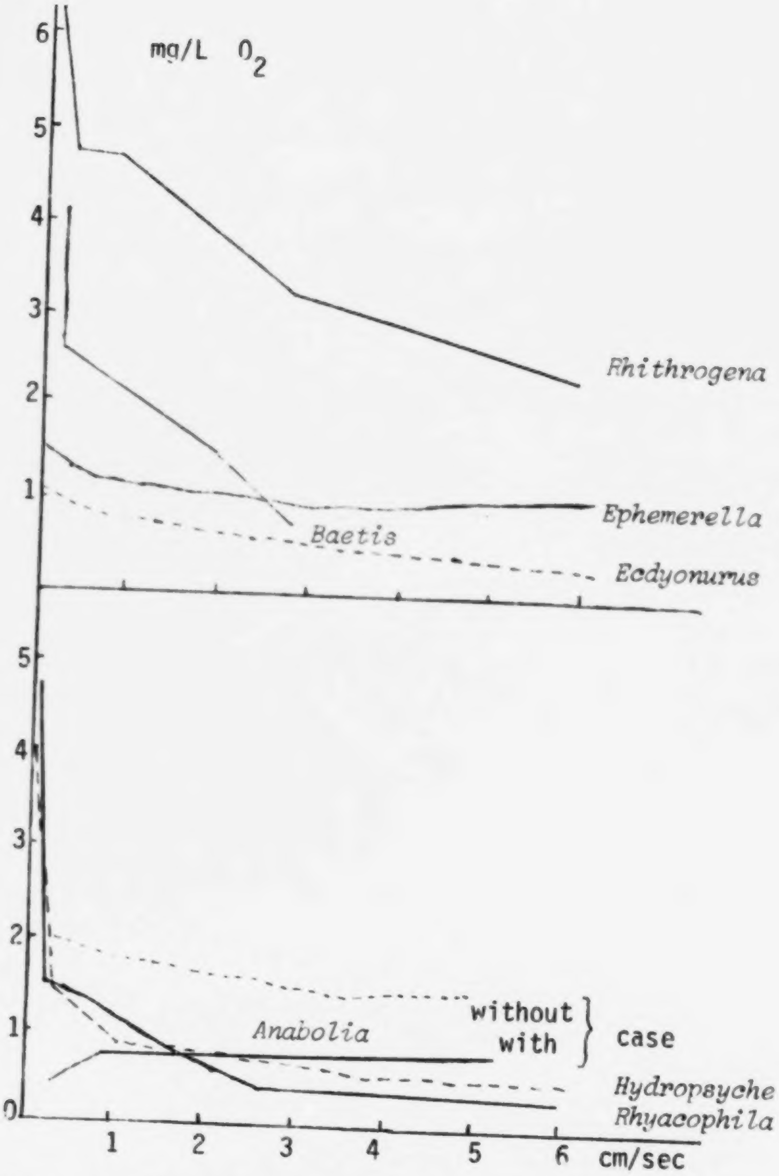

Figure 10: Relationship between current velocity and dissolved oxygen requirements for selected genera of aquatic insects. from: Hynes, H.B.N. 1972. The Ecology of Running Waters, University of Toronto Press, 555 pp.

begun to flow in the stream, reinvasion by fish was delayed by the absence of food organisms. It was not until the aquatic invertebrates had become reestablished that fish could successfully inhabit the stream.

While there are ample investigations concerning the minimum lethal oxygen concentrations for numerous aquatic animals, Macan (1963) warns that the lethal concentration is not the limiting factor in terms of oxygen depletion. Partial oxygen depletion can have serious effects.

> "The implication...that the incipient limiting point is always below saturation concentration, in other words that, under natural conditions the upper limit to activity is always set by the power of the animal to take up oxygen and never by the amount available must be avoided."

Doudoroff and Shumway (1967), in their discussion of attempts to establish water quality criteria, emphasize the problem reported above. They recommend that biologists refrain from specifying any particular dissolved oxygen level as a minimal requirement until clear guidelines and explicit definitions of terms are provided. No reduction in dissolved oxygen concentration is probably the only standard that would afford complete protection under all circumstances. Any lower or less restrictive standards applicable over wide ranges of temperature should be expressed as concentrations rather than as percentages of saturation.

Sedimentation: The problem of sedimentation is essentially a problem of organism-substrate relationships. As has been demonstrated, the more productive substrates are usually large particles. Sedimentation is likely to be a serious problem in the rivers of the Northern Great Plains. This is primarily a result of the climate and prevailing rainfall patterns in the region, as well as a function of the lithology, vegetation, and topography. The actual sediment yield per unit area is greatest where the annual precipitation is around 38 cm per year (Langbein and Schumm, 1958). In areas receiving less total rainfall, there is simply not enough water to carry a significant amount of sediment; where rainfall is greater, the amount of vegetation increases to serve as a check to sediment movement. Thus, a large portion of the Northern Great Plains has the potential for high sediment yields.

In addition, the region is often subjected to very severe thunderstorms of limited areal extent. Such storms frequently occur in the tributary drainages without adding significant amounts of water to the main-stem itself until the tributary enters the stream. Under these conditions, especially where the main-stem is dewatered and the tributaries are not, the tributaries will be discharging large amounts of suspended sediment into a river which lacks the discharge and velocity to keep it in suspension (Bovee, 1973). Cordone and Kelley (1961) agree that the damage done by sedimentation occurs primarily when silt enters a stream at times other than storm periods when the water velocity is insufficient to carry the sediment in suspension.

The effects of sedimentation on the most productive habitat for the bottom organisms has been mentioned several times. Sediment can settle into the interstices between larger particles, therby filling the voids inhabited by many of the species. This leads to the "cemented" condition discussed by Percival and Whitehead (1929). Eventually, the original coarse substrate may be completely covered over by a smaller sediment size, which results in the overall decrease in the food production in that part of the stream. While sediment may be a natural material in rivers, its presence during non-erosional periods of flow results in deposition which is unnatural and damaging. In regions of scour, the amount of deposition of fine materials would normally be small. It must be assumed that to preserve the stream bed in its normal condition, normal relationships between discharge and sediment size and concentration should be maintained (Cordone and Kelley, 1961).

H. Biotic Factors

The preceeding sections have dealt primarily with influences of the physical environment on stream organisms individually. This section deals with species interactions which are primarily density related. As a stream is dewatered, there is less space, and possibly less food and substrate, to support the populations of benthos. Therefore, conditions will become more crowded, and certain interspecific relationships will become more intense.

Competition: Competition is defined as the common demand of two or more individuals for a resouce in short supply. The competitive exclusion principle states that two or more resource limited species having identical patterns of resource utilization cannot continue to co-exist in a stable environment (Collier, Cox, Johnson, and Miller, 1973). This principle implies the elimination of one or more of the competing species during competitive interaction. There are numerous examples of this process, but there are also many cases where two closely related species, obviously in competition with each other, continue to co-exist for long periods of time. In many of these cases, exclusion does not occur because the physical environment is unstable and one species is not continuously favored.

During periods of dewatering, with the concomitant changes in the stream's hydrology, certain groups may be favored over others. Mention has been made about the limitations imposed by temperature on the competitive relationships between closely related species. Warmer stream temperatures will favor warm water species over cold water species, resulting in the invasion of the warm water species into territory formerly occupied by the cold water species. Another example of this type was given by Sprules (1947) in his comparisons of bottom type. In Sprules' study it is apparent that

Chironomidae are able to use a rubble substrate, along with a number of other species. However, on sand, the population was almost totally Chironomidae, indicating that these organisms could better use the available resources of substrate than could other species.

An example of competition avoidance might be noted in Edington's (1968) study of net-spinning caddis larvae. While both Hydropsyche and Polycentropus utilize the same food source (planktonic drift), they harvest it by different methods. Under conditions of reduced velocity, and with the same plankton quality Polycentropus would be favored over Hydropsyche because it filters a larger area of water and requires a lower current.

While Larkin (1956) notes that freshwater environments offer few opportunities for specialization in fishes, the same may not be true for the macroinvertebrates. However, he comments that it is sometimes difficult to separate the role of interspecific competition from other phenomena. Many aquatic invertebrates show a considerable amount of specialization, which is reflected in their distributions. Any factor which differentially affects one of two populations contending for a common position in the community structure will then affect the distribution and abundance of the species.

Predation: One factor which can differentially affect one population compared to another is the presence of a predator. In this sense, the two species are competing in predator avoidance. The species which is easiest to catch will likely be selected against. Therefore, the behavioral adaptations of the species are important. For example, an insect which lives beneath a rock is likely to be harder to catch than one which is active and crawls around on top of the rock.

The density related aspect of predation concerns both the density of the prey and the density of the predators. Where more organisms are concentrated in an area, the probability that an individual will encounter a predator is increased. This phenomenon is magnified when the concentration of predators also increases. In this case, the resource in short supply would be suitable hiding places. A factor such as sedimentation would certainly limit the number of hiding places and might tend to favor one species over another.

Drift: Drift refers to aquatic or terrestrial insects which have released from the substrate and float in the current. The simplest form of drift is catastrophic drift, in which sudden or prolonged high discharges mechanically dislodge organisms from the substrate. There is little argument about the origin of this drift source.

Several researchers indicate that drift is density related, and may be linked to interspecific or intraspecific competition. Dimond (1967) studied the bottom fauna and the fauna of the drift in streams treated with DDT at various times in the past. He found that recovery of the bottom fauna was rapid, but that return to normal drift patterns lagged recovery of the benthos by two years. The relationship between the number of organisms in the drift and increased bottom standing crop during recovery was curvilinear, indicating that the rate of drift increased as the bottom become more crowded. Several competitive interactions may be involved in this phenomenon. Competition for food in dense populations could lead to more searching behavior by the animals, which would make them more susceptible to dislodgement. Territorial behavior might be practised and individuals without territories comprise the drift. High population densities might cause animals to spread into marginal habitats which are prematurely vacated.

Thus, the question becomes one of whether drift is an active behavioral process or accidental. Evidence exists for both explanations.

Most benthic invertebrates are negatively photoactic and exhibit their greatest activity during periods of darkness. A number of studies have demonstrated that drift rates increase at night (Pearson and Franklin, 1968; Elliott, 1968, 1971) indicating a considerable amount of accidental drifting. Elliott (1967) suggests that drift density reflects the degree of competition and the activity of animals moving across exposed areas where they are more subject to dislodgement. Since only a small portion of the total population in the benthos becomes involved in the drift, he feels that the organisms are more likely jostled loose or simply lose their grip, rather than actively detaching from the substrate.

Minshall and Winger (1968) observed drift in a small stream below an irrigation diversion, and concluded that entry into the drift was an active behavioral process contrary to the normal avoidance reaction to light. They found that the number of animals in the drift was inversely proportional to the discharge but the cause of this increase was not determined.

In a study designed to treat the disagreement over the density relationships and drifting, Pearson and Kramer (1972), related drift rates directly to the biomass of the benthos over an entire year, but found that drift in the two species studied was density related only during the period of fastest growth.

Pearson and Franklin (1968) found that illumination, population density of all bottom organisms, and temperature were significant factors in the drift rate of Baetis nymphs and Simulium larvae. Turbidity and water level fluctuations affected drift indirectly through their effects on illumination and population density, respectively. Waters (1961, 1962) felt that drift was density related, and that it functioned to remove organisms from areas in which the carrying capacity had been reached. In one study (Waters, 1961) found that there was little correlation between drift rates and population density unless the collections were divided into groups as functions of aquatic longevity. Short living forms tended to show a stronger correlation. Perhaps these short living forms produced large numbers of offspring and intraspecific competition was the driving force behind these drift rates. In later work Waters (1969) postulates that drift is a function of production rates, which does not seem to conflict with the findings of Elliott or Pearson and Kramer.

The evidence presented indicates that at least to an extent, drift is density dependent, and is probably a reflection of the amount of competition in a given area. Other research indicates that drift rates for some species are an indication of productivity, as organisms tend to drift more readily when they are growing rapidly. Since drifting organisms are the primary source of food for many fish species living in pools, the relationship between streamflow and drift rates is important.

It can certainly be argued that a reduced discharge would result in the crowding of invertebrates in the remaining habitat. However, only one limited study (Minshall and Winger, 1968) has shown an increase in drift rates due to decreased discharge. In this case, the stimulus was not competition, but more likely an avoidance reaction to suddenly reduced water levels. Elliott (1973) presents evidence that a slow decrease in discharge results in a decrease in drift rates and total biomass in the drift. It is possible that under conditions of reduced discharge, velocity over riffle areas is not high enough to remove foraging invertebrates from the substrate.

Thus, as discharges are decreased, two mechanisms operate to reduce the rate of drift. As the productivity of the riffle is lowered, drift rates will decline; and as water velocity decreases over riffle areas, fewer animals are swept from the substrate. This will result in the ultimate decrease in the food biomass which is removed from riffle areas. Since drift is a major direct food source, and is the major pathway by which food in pool areas is replenished, a decrease in the amount of invertebrate drift would be a major impact on the carrying capacity for fish in the stream.

APPENDIX II

HABITAT PREFERENCES

A. Acipenseridae II-156
B. Polyodontidae II-157
C. Hiodontidae II-157
D. Salmonidae II-157
E. Esocidae II-159
F. Cyprinidae II-160
G. Catostomidae II-164
H. Ictaluridae II-166
I. Centrarchidae II-168
J. Gadidae II-170
K. Percidae II-171

Habitat preferences of fish include parameters of successional distribution and local distribution. Viewing habitats in terms of specific preferences of individual species affords a means of explaining observed distributions and of predicting species most likely to be affected by changes in the hydrologic regime of the river.

Hooper (1973) describes the locations and conditions where an animal lives as a microhabitat. Stream dwelling fish must maintain a position in a moving medium, and therefore, the place selected by a fish as a resting area is important as the focus from which it may move into other microhabitats. For example, a fish may rest in the protection of a submerged log, make feeding forays into swift water, and then return to the log. This concept is defined by Gerking (1953) as a home range. Gerking considered that in streams with a riffle-pool development, each pool was essentially an isolated unit containing a population of its own. The chances are great, that once a fish becomes established in an area, it will remain there for most of its lifetime. A territory might be described as that portion of the home range which is defended by the fish. Thus, a home range might include several overlapping microhabitats, each with a particular function, one or more of which is defended by the fish. Some species, however, are extremely transient and are not at all territorial.

A great deal can be learned about the habitat of a fish species simply from its appearance. Hubbs (1941) discusses speciation in stream fish as a series of adaptations to environmental conditions. In adjusting to these conditions, fish from diverse groups have often made "parallel adaptations" or have made nearly the same speciational response to the conditions to which they have been subjected.

Fish which normally live in swift water usually have streamlined bodies, often with sharp entering wedges (flat or pointed head), slender tails, and expansive and falcate fins. They are designed for bottom life and bottom feeding, with flat ventral surfaces and an inferior, horizontal mouth. An example of a fish ideally designed for life in a strong current is the sturgeon.

Fishes which live primarily in slow pools tend to have larger and more oblique mouths which are better designed to engulf food organisms at various water levels. These fish are often deep bodied and heavy. An example of adaptations to pools is the largemouth bass.

Reported here are the habitat preferences of many of the species found in rivers of the Northern Great Plains. These data tend to be extremely general compared to the detailed microhabitat work outlined by Giger and Hooper. However, inferences will be made where possible in an attempt to quantify the characteristics of each habitat type. This material refers primarily to I+ and older age classes. Habitats of young of the year are different and largely unknown.

A. Acipenseridae

There are two species of sturgeon present in larger rivers of the Northern Great Plains region, Scaphirhynchus platorhynchus (shovelnose sturgeon) and S. albus (pallid sturgeon). The preferred habitat for both species is in large rivers, usually in the main channel, where the current is strong and the bottom comprised of coarse sand (Brown, 1971; Bailey and Cross, 1954; Zhadin and Gerd, 1961). Bailey and Cross note that S. platorhynchus is normally found over sand or gravel, and may lie over a silt bed if the current is strong enough to be swept clean. In order for this type of bottom to be maintained, the current velocities would probably be in the range of 18 to 150 cm/sec (0.6 to 5 ft/sec) with the probable inhabited range from about 30 to 60 cm/sec (1 to 2 ft/sec). Both species can tolerate high turbidities, but are apparently eliminated by the combined effects of reduced velocities and sedimentation (Bailey and Cross, 1954; Krumholtz, et. al., 1962).

B. Polyodontidae

While paddlefish do inhabit large rivers, they appear to reside in main-stem reservoirs in the Northern Great Plains (Robinson, 1966; Elser, 1973). Stockard (1907) states that the paddlefish frequents the deeper parts of lakes, and is almost never found in lakes less than 3.1 meters in depth (10 ft). It apparently prefers a mud bottom, being found only rarely over sand. The streamflow parameter most likely to affect the paddlefish is the magnitude and duration of spring discharge during its spawning migrations.

C. Hiodontidae

The goldeye is normally found in large rivers, and is quite tolerant of high turbidities. In Montana, its distribution is apparently restricted by water temperature. The goldeye is generally not found in streams with summer water temperatures less than about 16° C (60° F) (Brown, 1971). Coker (1930) notes that the goldeye frequents swift, open water and is usually not found in impoundments on the Mississippi River. Relatively little is known about the microhabitat preferences of this species.

D. Salmonidae

Three species of salmonids are found in the colder portions of streams in the Northern Great Plains of Montana. The brook trout typically prefers small streams or ponds where the bottom is sand or gravel, whereas brown and rainbow trout are commonly found in larger rivers. The brown and the rainbow can apparently tolerate warmer conditions than can the brook trout (Brown, 1971). Hooper (1973) states that the brook trout chooses points in the stream where there is slow water overlain by swift water as resting areas, and is intimately associated with in-stream cover. Modal velocities of focal points ranged from 1.8 cm/sec to 15.3 cm/sec (0.06 to 0.53 ft/sec), with maximum velocities above the focal points ranging from 18.3 to 36.6 cm/sec (0.6 to 1.2 ft/sec).

Brown trout occupy resting areas with definite laminar flow, with focal points similar to those of brook trout (Hooper, 1973). Study fish occupied resting microhabitats in an experimental flume with a velocity range of 12.2 to 21.4 cm/sec (0.4 to 0.7 ft/sec). Turbulence, light, water depth, spatial limits, cover, and direction of flow also influenced selection of sites. Hooper attributes the differences in velocity preferences between brook and brown trout partially to variations in experimental techniques. However, different species probably have different velocity preferences. Giger (1973) lists the preferred velocity range for brown trout between 3.7 and 6.4 cm/sec (0.12 to 0.21 ft/sec). Part of the discrepancy between the suggested preferred velocities mentioned by Giger and Hooper might be caused by recording velocity measurements made at different depths in the water column. Hooper suggests that stream velocities should be measured near the bottom.

The Oregon State Game Commission recommends pool velocities of 9.1 to 24.5 cm/sec (0.3 to 0.8 ft/sec) for salmonid rearing flows (Thompson, 1972). Hooper (1973) states that for trout in general, areas with velocities between 9.1 and 31 cm/sec (0.3 to 1.0 ft/sec) are preferred for resting.

While depth criteria have not been defined for trout in general, the depth of pools appears to be very important in terms of fish size. Wesche (1973) considered depths greater than 15.3 cm as suitable for brown trout, but larger trout appear to prefer deeper pools. Gunderson (1966) found that stream sections lacking deep pools and adequate cover contained only fingerling trout, while stream sections with deep pools separated by riffle areas contained much larger trout. Giger (1973) lists the optimum pool depth for cutthroat trout as 0.4 to 1.1 meters (1.3 to 3.7 feet) depending on age and size.

E. Esocidae

The habitat of the northern pike is usually in lake bays, but it is also common in pools and backwaters of streams where vegetation is present. Parsons (1959) describes the habitat of a closely related species, the muskellunge, as rocky and fast-flowing streams with clear water. Bottoms of pools are often covered with sand or silt, indicating substantial pool velocities. The muskellunge chooses cover along the edge of the stream in patches of aquatic vegetation, beside submerged roots or branches, or in patches of shade. They will usually remain in these areas, darting out to capture a fish passing in the open water, and then returning to the resting area. Many of these fish preferred pools with plentiful sunlight but with shaded areas along the edge. This situation would be advantageous to a sight-feeder such as the pike. Eddy and Surber (1943) note that the pike prefers areas with low current velocity, and is not averse to warm or muddy water. Tubb, Copes, and Johnson (1965) found the northern pike in pools with bottom types ranging from rubble to mud, but never in depths less than 0.61 meter (2 feet). This depth should be considered marginal as most of the pools had internal depth ranges from 0.61 to 1.5 meters (2 to 5 feet).

It is of interest to note that the appearance of the northern pike is among the last in many longitudinal successional sequences. This would indicate that the pike prefers deeper and slower waters. Huet (1959) classified the pike as a member of the "grayling zone" but noted that it became increasingly abundant as the stream size increased. The grayling zone was characterized as being fairly rapid with a riffle and pool arrangement. The abundance of pike increased as the depth of water exceeded 2 meters in pools. Since the pike is strongly linked to in-stream cover, and is apparently found near the edge of the stream, it is possible that pools which are not at least a meter deep at their centers are too shallow at their margins for the pike to use the cover available. In other words, the water must be about 0.6 meters deep at the edge of the pool.

F. Cyprinidae

As a group, the minnows occupy a wide variety of habitats. In many streams, the minnow fauna alone makes up a great deal of the longitudinal successional pattern of the stream.

Generally associated with extreme headwater regions with moderately warm summer water temperatures is the creek chub (Semotilus atromaculatus). This species is truly a creek fish, and has been reported to live in rivulets only 2.5 to 15 cm deep and less than a meter wide (Thompson and Hunt, 1930). There is apparently an upper limit to the size of pools in which the creek chub thrives as it is usually more abundant in small streams than in large ones (Starrett, 1950a). Tubb, et. al. (1965) found that this species disappeared as pool depths exceeded 1.5 meters (5 feet). Larimore and Smith (1952) noted that the creek chub was most abundant in pools 0.1 to 0.6 meters in depth (4 inches to 2 feet), with a moderate current.

Another species associated with shallow water and swift current is the longnose dace (Rhinichthys cataractae). The adults of this species are typical riffle dwellers. Gee and Northcote (1963) found that all age groups of longnose dace were most commonly collected in water depths less than .3 meter (about 1 foot) with velocities faster than 0.5 m/sec (1.6 ft/sec). Young of this species retreat to deeper water at night, while the adults tend to stay in shallow areas.

The sturgeon chub (Hybopsis gelida) has a rather restricted habitat. It is found in shallow water riffles over gravel areas, where the current is moderate to strong. Its habitat is probably similar to that of the longnose dace, but the current velocity may be somewhat slower (Brown, 1971).

Also associated with shallow areas are the pearl dace (Semotilus margarita), and the flathead minnow (Hybopsis gracilis). The habitat of the pearl dace is similar to that of the creek chub, but the flathead minnow exhibits a very wide range of habitat tolerances. It is found in shallow as well as deep, swift or slow waters, over bottoms ranging from mud to rubble (Brown, 1971).

The fathead minnow (Pimephales promelas), is found in waters which are shallow to moderately deep, but always with little current. Carlson (1967) found this species in pools ranging in depth from 15.2 cm to 61 cm (0.5 to 2.0 feet). Tubb, et. al. (1965) found fathead minnows in depths from 15.2

to 152 cm (0.5 to 5 ft) in depth. These minnows are intimately associated with aquatic vegetation, either submerged algae or emergent higher plants. Its habitat tolerances are quite wide, but its range appears to be limited by its inability to successfully compete with other species (Starrett, 1950a; Carlson, 1967).

Associated with shallow to moderately deep waters are the golden shiner (*Notemigonus crysoleucas*), the sand shiner (*Notropis stramineus*), and the lake chub (*Couesius plumbeus*). The golden shiner can reach sizes up to 30 cm in length, and the depth of water in which it is found is probably a function of its size. This species is rarely found in the absence of aquatic vegetation (Hubbs and Cooper, 1936). Larimore and Smith (1963) found golden shiners in pools of moderate velocity which were 0.6 to 1.2 meters (2 to 4 ft) deep, but not in pools less than 0.6 meters deep. Tubb, et. al. (1965) found this species most commonly in pools which were 0.45 to 1.52 meters deep (1.5 to 5 ft), with bottoms composed of silt or mud, which would indicate a rather slow current.

The sand shiner was studied in detail by Summerfelt and Minckley (1969) in Kansas streams. They described its habitat as being diverse, but the minnow was most often found in depths ranging from 6.1 cm to 43 cm (0.2 to 1.4 ft). It was most often found over a sand bottom in areas with little overhead cover. Tubb, et. al. (1965) did not find this species in less than 0.9 meters of water, but none of their shallow pools had sand bottoms.

The lake chub is widely distributed in Montana, and apparently prefers low gradient creek habitats. Further information concerning the lake chub was not found.

The emerald shiner (Notropis atherinoides) is reported by Brown (1971) to prefer larger streams or their impoundments. Minckley (1963) found it in stream areas with conditions similar to those occupied by the sand shiner. The findings of Tubb, et. al (1965) seem to agree with those of Minckley. They found the emerald shiner in only one pool, which was 0.91 m (3 feet) deep and had a sand bottom. Like the sand shiner, the emerald shiner prefers open water away from vegetation.

Stream pools with moderate depths and velocities are likely habitats for three minnows of the genus Hybognathus, the plains, brassy, and silvery minnows. Brown (1971) states that little is known about the life history of the plains minnow (H. placitus), but that it is probably much like that of the silvery minnow (H. nuchalis). Brown reports that the silvery minnow seems to prefer larger rivers over creeks or impoundments, and is often abundant in pools ranging in depth from 0.61 to 1.52 meters in depth (2 to 5 feet). Minckley (1963) noted that the silvery minnow was rare in Doe Run, Kentucky, but that the greatest numbers were found in deep pools near streamside debris such as roots or drift. Larimore and Smith (1963) found this species most commonly in pools .46 to .91 meters (1.5 to 3 feet) in depth, with moderate currents and sand or sand-silt bottoms.

The brassy minnow (Hybognathus hankinsoni), apparently prefers clear, slow streams with sandy bottoms. Tubb, et. al. (1965) found the brassy minnow only in limited areas, in pools 0.91 to 1.52 meters (3 to 5 feet) in depth, with moderate currents. Starrett (1950a) noted that the brassy minnow occurred in limited numbers in streams of all sizes, but was most abundant in inlets of tributaries and pools.

Two species of cyprinids, the redbelly dace (*Phoxinus eos*) and the carp (*Cyprinus carpio*), are generally found in sluggish water which is moderately to very deep. The redbelly dace is confined primarily to smaller creeks where it lives in sluggish, mud-bottomed pools (Hubbs and Cooper, 1936).

Ecologically, the carp may be one of the most important species in a river system. The carp has a wide range of tolerances and is a very successful competitor with all other species. Brown (1971) states that the carp prefers moderately warm and shallow water where aquatic vegetation is plentiful. Thompson and Hunt (1930) found the carp most abundant in mud-bottomed pools which were 0.91 to 2.45 meters (3 to 8 feet) deep, and had sluggish currents. Larimore and Smith (1963) found young carp in shallow pools less than 61 cm (2 feet) deep, with moderate velocities, but found adults mainly in pools ranging from 0.91 to 2.45 meters (3 to 8 feet) in depth. Sigler (1958) states that carp generally prefer the deepest parts of the river, but can thrive in depths of .91 to 1.2 meters (3 to 4 feet) provided there is sufficient cover. The carp avoids currents at all times except during spawning.

G. *Catostomidae*

The shorthead redhorse (*Moxostoma macrolepidotum*) apparently has the narrowest range in habitat preference of all the members of this family. This species prefers swift, shallow water with rubble or gravel bottoms (Meyer, 1962). Larimore and Smith (1963) stated that the *Moxostoma* species were most often found in shallow pools, ranging in depth from 9.1 to 61 cm (0.3 to 2.0 feet), with moderate currents. Similar findings were reported by Minckley (1963) who noted that the shorthead redhorse occurred frequently at the foot of riffles. Krumholtz, Charles, and Minckley (1962) stated that the redhorse was essentially limited to the upper 160 km of the Ohio River, which may reflect is requirement for shallow water, or its aversion to turbidity and pollution.

Another species with rather restrictive habitat preferences is the blue sucker (Cycleptus elongatus). This fish prefers deep waters of large rivers with high current velocity (Brown, 1971). Few reports mention the capture of the blue sucker, indicating its preference for large rivers and the most difficult habitat to sample. We speculate that the preferred habitat of the blue sucker is slightly deeper and slower than that of the shovelnose sturgeon.

Two species of catostomids show a fairly wide range of habitat preferences. These are the longnose sucker (Catostomus catostomus) and the white sucker (C. commersoni). These species are found in headwater streams, large rivers, and impoundments. The white sucker is often considered a pioneer species because of its wide range of tolerances. It has been found in riffle areas in water less than 15 cm (6 inches) deep, in pools ranging from 15 to 91 cm (0.5 to 3.0 feet) in depth, and in pools .91 to 2.45 meters deep (Thompson and Hunt, 1930; Larimore and Smith, 1963; Tubb, Copes, and Johnson, 1965). While demonstrating a wide range of habitats, these species apparently do not select areas of very swift current, such as rubble bottomed riffle areas. Thompson and Hunt, 1930).

Habitat preferences of the river carpsucker (Carpiodes carpio) and the smallmouth buffalo (Ictiobus bubalus), are also variable. The carpsucker is found in most streams and reservoirs within its range regardless of their size, velocity or turbidity (Brown, 1971). However, it is known to prefer deeper pools and backwaters. Eddy and Surber (1943) state that the carpsucker is probably restricted to sluggish parts of streams. Minckley (1963) indicates that the habitat preferences of both the carpsucker and the smallmouth buffalo are probably the same as those of the carp.

The smallmouth buffalo prefers swifter water than its close relative, the bigmouth buffalo (Ictiobus cyprinellus) (Coker, 1930). The smallmouth buffalo will also tolerate shallower water than will the bigmouth. Thompson and Hunt (1930) note that I. cyprinellus is found primarily in mud-bottomed pools 0.9 to 2.45 meters (3 to 8 feet) deep, usually containing submerged logs and partially shaded by overhead cover. In the Sheyenne River of North Dakota, the bigmouth buffalo was rare and not found in pools less than 2.1 meters (7 feet) deep (Tubb, et. al., 1965).

H. Ictaluridae

The black bullhead (Ictalurus melas) is often found in shallow pools but is also abundant in deep pools and backwaters. This species apparently selects water areas which have slow or sluggish currents, and is often found over a mud bottom (Larimore and Smith, 1963; Thompson and Hunt, 1930). Tubb, et. al (1965) found black bullheads in pools as shallow as 30.5 cm (1 foot), but Larimore and Smith (1963) found it most commonly in pools greater than 61 cm (2 ft) in depth. Minckley (1963) noted that this species was most often taken in the deeper pools of the stream he studied.

The yellow bullhead (Ictalurus natalis) exhibits habitat preferences similar to those of the black bullhead. Krumholtz, Charles, and Minckley (1962) stated that the yellow bullhead was found over the entire length of the Ohio River, indicating a wide range of environmental tolerances.

As its name implies, the channel catfish (Ictalurus punctatus) prefers areas of swift current, but it is not restricted to these areas (Coker, 1930). Thompson and Hunt (1930) found the young of this species inhabiting very swift water in rocky riffles where the water depth ranged from 5 to 38 cm (2 to 15 in). The adults were more commonly found in pools ranging from 31 to 120 cm (1 to 4 ft) in depth, with moderate currents, and in deep pools 0.91 to 2.45 meters (3 to 8 ft) deep, with little current. Welker (1967) found that while the channel catfish does prefer a current, excess current or too shallow water will limit the distribution of the species. He found that catfish in the Little Sioux River in Iowa apparently preferred pools 1.5 meters (5 ft) deep in unchannelized sections over channelized sections which did not contain pools deeper than 0.75 meter (2.5 ft).

A small member of the catfish family, the stonecat (Notorus flavus) appears to have very specific habitat preferences. Its distribution in streams is limited primarily to riffles or rapids over large, loose rocks, where the current velocity is swift. Johnson (1965) found the stonecat most frequently in rubble bottomed riffles where the mean depth of water over the riffle was greater than 15 cm. Larimore and Smith (1963) note that it is most abundant in boulder or rubble rapids where water depth is between 8 and 45 cm. Clay (1962) states the stonecat is extremely sensitive to sedimentation, and is most successful where the current is sufficient to prevent the accumulation of sediment. The inferred current velocity for such conditions would probably be in the range of 50 to 150 cm/sec (1.5 to 5 ft/sec).

I. Centrarchidae

As in many other families, a wide range of preferences is exhibited by the family as a whole. These fishes tend to use home areas and focal points extensively, and will often return to their home areas when displaced (Gerking, 1950b; Hasler and Wisby, 1958; Fajen, 1962). Many of the species have quite definite habitat preferences and are frequently very territorial.

The rock bass (*Ambloplites rupestris*) is commonly found only in the Tongue River in Montana, but is known to frequent other rivers in the Great Plains region. The preferred habitat for this species is in moderately warm, clear, rock-bottomed streams (Brown, 1971). The rock bass is intimately associated with some feature of in-stream or over head cover. Scott (1949) found the rock bass most commonly near partially submerged logs or beneath undercut banks or streamside vegetation in moderate currents of water 0.61 to 1.2 meters (2 to 4 ft) deep. Scott (1949) and Gerking (1953) both note that the home range of the rock bass is quite small, apparently about half the size of the wider ranging smallmouth bass. Johnson (1965) found fairly large numbers of rock bass fry in pools which were only about 20 cm (8 in) deep, but the greatest number of adult rock bass were in pools 0.46 to 0.61 meter (1.5 to 2.0 ft) deep (the deepest pools in the stream), in reaches of lowest gradient (.0013 to .0019 m/m).

The smallmouth bass (*Micropterus dolomieui*) is basically a cool water species and prefers stream areas with sufficient velocity to maintain extensive riffle areas and clean swept bottoms. Like the rock bass, the smallmouth bass makes extensive use of cover, especially in faster water (Haines and Butler, 1969; Hubbs and Bailey, 1938). The habitats of the smallmouth bass and the rock bass probably overlap to an extent (Hallam, 1959). The association between velocity and smallmouth bass distributions has been demonstrated by Trautman (1942). He found that streams which meandered greatly and contained alternating pools and riffles were prime smallmouth bass habitats. The distribution of smallmouth bass was correlated with stream gradient, with few bass being found in stream areas with gradients lower than 0.75 m/km or greater than 4.75 m/km (slope = .00075 and .00475 respectively). The greatest numbers of bass were located in stream areas with gradients ranging from 1.3 to 3.8 m/km (.0013 and .0038 respectively). Minckley (1963) states that in many ways, the preferred habitat of the smallmouth bass is similar to that of the rainbow trout. He was also able to correlate bass distribution with gradient in a small stream in Kentucky. Thompson and Hunt (1930) noted that smallmouth bass were typically found in moderately deep, smooth flowing reaches with current sufficient to maintain a bottom of sand and gravel. These reaches were usually between .31 and 1.2 meters in depth (1 to 4 ft).

The largemouth bass (Micropterus salmoides) generally cannot tolerate the swift currents preferred by the smallmouth and rock basses (Curtis, 1949). The habitat of the largemouth bass is quite similar to that of the bluegill (Lepomis macrochirus), and they are often found associated with one another (Minckley, 1963; Larimore and Smith, 1963; Thompson and Hunt, 1930). Thompson and Hunt found both species most frequently in sluggish, mud-bottomed pools 0.91 to 2.5 meters (3 to 8 ft) deep. Mraz, Kmiotek, and Frankenberger (1961) note that largemouth bass make frequent and extensive use of overhead cover and are seldom found at depths greater than the deepest water in which rooted vegetation will grow.

The preferred habitats of the green sunfish (Lepomis cyanellus), pumpkinseed (L. gibbosus), and the white, and black crappie (Pomoxis annularis and P. nigromaculatus), are similar to those of the largemouth bass and bluegill. However, Thompson and Hunt (1930) found the white crappie and green sunfish in habitats often considered too shallow for largemouth bass (.31 to 1.2 meters). These species all show some tendency to avoid currents, and in general, are associated with deep, sluggish water. Larimore and Smith (1963) stated that the preferred habitat of the white crappie was in pools greater than 1.2 meters (3 ft) in depth, which normally have mud bottoms.

J. Gadidae

This family is represented by only one species, the burbot (Lota lota). The burbot is a cold water fish which is well adapted to a swift water habitat. Zhadin and Gerd (1961) state that the burbot is a member of the Lithorheophilic biocenosis, which is composed of animal and plant species which are adapted for life on stony bottoms in a fast current. However, several authors report the presence of burbot in lakes (Bonde and Maloney, 1960; Bjorn, 1940) so the burbot must be able to utilize a fairly wide range of habitats. In some cases, the habitat of the burbot overlaps that of the white sucker (Chen, 1969). Chen also notes that the burbot seems to prefer turbid water. One habit of the burbot which sets it apart from most other species is that it is most active during the winter rather than spring and summer (Brown, 1971).

K. Percidae

Three species of this family are of particular interest, the yellow perch (Perca flavescens), the walleye (Stizostedion vitreum), and the sauger (S. canadense).

The yellow perch is most often found in lakes, but is also abundant in backwaters of larger rivers. It is seldom found in small streams (Herman, et. al., 1959; Eddy and Surber, 1943). Relatively little is known about the flow requirements of this species, but its habitat preferences are thought to be quite variable. Herman, et. al. states that the perch prefers clear water with moderate amounts of vegetation, and may be found in the same habitats as carp.

The walleye and sauger are closely related and sympatric species, both showing a high degree of negative phototropism. However, they occupy quite different ecological niches. The walleye prefers clear water and is primarily crepuscular when feeding. The sauger grows well in turbid water and feeds more actively during the day. The variation of the behavior and habitats of the two species has been correlated with structural differences in their eyes (Ali and Anctil, 1968). Both species have eyes which are most effective under conditions of reduced light. The walleye is known to be dazzled by bright light, which causes it to retreat to deeper water or shady places during the day. Eschmeyer (1950), while studying the life history of the walleye, described the extreme negative phototropism exhibited by this species:

> "Attempts to escape light often result in glancing collisions with rocks or other obstacles, and occassionally a fish may nearly beach itself in its efforts to flee."

Tubb, et. al. (1965) found the walleye in pools ranging from 0.91 to 5.5 meters (3 to 18 ft) in depth, but most commonly in pools greater than 2.5 meters (8 ft) deep. The sauger was taken in only one pool which was 2.5 meters deep.

APPENDIX III

SPAWNING REQUIREMENTS

Species Which Build Nests or Redds III-174
Species Which Do Not Build Nests or Redds III-180

This section discusses the spawning requirements for a diverse group of fishes. Requirements in terms of hydrologic and water quality parameters will be given in as great detail as is possible. However, for some species it will be necessary to again infer hydrologic dimensions from qualitative observations. This section also attempts to determine those species which would least be affected by reduced discharge, and which would probably enjoy a competitive advantage over other species under these conditions.

Spawning behavior can be broadly classified into two major groups: those species which build some type of nest, exhibit territoriality, and show some general form of parental care; and those which do not. Species included in the former group are the salmonids, the centrarchids, and the ictalurids. Several species of cyprinids also build nests and guard their eggs. Included in the latter group are the sturgeons, the paddlefish, the northern pike, most of the cyprinids, the suckers, and the perch family. Streamflow requirements are no less stringent for species which do not build nests. Many so-called "broadcast" spawners require specific substrates or hydrologic conditions for successful reproduction.

Species Which Build Nests or Redds

The salmonids excavate holes in sand or gravel bottoms during spawning. These holes are called redds, and are somewhat different in function than true nests. Eggs are deposited in the excavated bottom, fertilized, and covered over with gravel. Streamflow can affect hatching success in redds in ways which are not so deleterious in nests. Because developing eggs require oxygen, a continuous flow of fresh water is required around the eggs.

Percolation of freshwater through the spawning grounds is a function of water velocity and depth above the redd, and is also affected by silt settling into the interstices in the gravel bed. This sedimentation essentially seals the bottom and thus prevents the vital exchange of water within the bed (Silver, Warren, and Doudoroff, 1963; Peters, 1967).

Therefore, the streamflow requirements for spawning salmonids are quite definitely defined. Hooper (1973) summarizes the preferred spawning areas for trout as follows:

1) Brook trout are fall spawners. Spawning is apparently induced by day length and water temperature. Peak brook trout spawning occurred after the minimal water temperature had dropped to between 2.8° and 6.7° C (37° and 44° F). Nests are usually located in fairly rapid currents and usually at the lower ends of pools.

2) Brown trout are also fall spawners. Water temperatures during the peak spawning run usually range from 6.1° to 12.5° C (43° to 55° F). Brown trout apparently prefer gravel ranging from .63 to 3.8 cm (.25 to 1.5 in) in diameter. Current velocity over the majority of redds studied was within the range of 39.6 to 51.7 cm/sec (1.3 to 1.7 ft/sec), as measured 7.5 cm (.25 ft) from the bottom. Spawners seem to prefer shaded areas.

3) Rainbow trout spawn during the spring. The optimum spawning temperature for rainbows is 11.1° C (52° F), but ranges from 7.2° to 13.3° C (45° to 56° F). Preferred gravel size was .63 to 3.8 cm (.25 to 1.5 in) in diameter, with preferred velocities between 42.6 and 82.0 cm/sec (1.4 and 2.7 ft/sec).

The California Game and Fish Department defines spawning areas for resident trout as those areas of stream bottom which have:

1) Water velocities of 15.5 to 91 cm/sec (0.5 to 3.0 ft/sec), as measured 6 cm (0.2 ft) from the bottom.

2) At least a two square meter (about 22 square feet) section of bottom consisting of gravel from pea size to 7.6 cm (3 in) in diameter.

3) A water depth over 15.5 cm (0.5 ft) (Hooper, 1973).

In general, the fecundity of the salmonids is quite low. Brown (1971) states that female brown, and rainbow trout produce about 800 to 1200 eggs per pound of fish. Brook trout females average only between 300 and 400 eggs, but larger individuals may produce 1000 to 2000 eggs. This number is quite small in comparison with other species.

The creek chub (Semotilus atromaculatus) constructs what can best be described as an intermediate between a nest and a redd. Spawning usually occurs in clear streams on a bottom of coarse gravel, and usually at the head of rapids. The completed nest is a conspicuous ridge of gravel about 15.5 cm (1 ft) wide, 5 to 7.5 cm (2 to 3 in) deep, and from .31 to 5.5 m (1 to 18 ft) long, in line with the current. Eggs are laid in the cavity just below the gravel ridge during the many visits of one or more females to the nest. Between visits, the male busily carries stones to the nest to cover fertilized eggs (Hubbs and Cooper, 1936). The creek chub will not spawn in still water, and is extremely territorial (Carbine, 1939). The fecundity of the creek chub is quite high, with females producing from 3000 to 4000 eggs each (Brown, 1971).

Members of the family Centrarchidae are true nest builders, although certain species tend to be more conscientious than others about the construction. The nests are generally saucer shaped depressions which have been fanned out of the substrate by the male. They are usually near in-stream cover. Unlike the redds of the salmonids or the creek chub, fertilized eggs are not covered over. The nests are actively guarded by the males of the species, which hover over them and gently fan currents across the developing eggs. This fanning process accomplishes two functions. It keeps silt from settling on top of the eggs, and it provides a current for the oxygenation of the developing eggs. Thus, current velocity is not directly important to spawning centrarchids. The most serious damage is done to developing centrarchid eggs by low or rapidly fluctuating water temperatures, sedimentation in excess of the amount the male can fan away from the nest, low water levels, wind and wave action, or conditions which drive the defending parent away from the nest.

Little information was found concerning the spawning sites of the rock bass, but it is assumed that they are not much different from those of the smallmouth bass. The smallmouth bass generally spawns over coarse sand, gravel or rubble bottoms, in .91 to 1.8 m (3 to 6 ft) of water (Curtis, 1949; Hubbs and Bailey, 1938). Nests are usually located in areas protected from direct wind and wave action, and which contain submerged rocks or fallen trees (Tester, 1931). Nest building begins when the water temperature range is between 15° and 18.3° C (59° and 65° F). Hubbs and Bailey state that spawning begins when the temperature reaches 15° C (59° F) if the temperature rises slowly, but that if the water is warmed rapidly, spawning does not start until the temperature reaches 18.3° C (65° F). Noting this phenomenon, Reynolds (1965) suggests that water levels may be more important than temperature in initiating spawning. The fecundity of the smallmouth bass is fairly high, with individual females laying about 7000 eggs per pound of fish (Brown, 1971).

The largemouth bass and bluegill are not so particular in selecting spawning sites. Almost any type of bottom material is suitable, so long as it can be swept clean to reach some hard surface. The largemouth bass prefers to lay its eggs on roots or twigs to which the eggs can adhere.

Spawning for both species normally takes place in .31 to 1.2 m (1 to 4 ft) of water, but extremes from 25 cm to 3.7 m (10 in to 12 ft) have been observed in the largemouth bass (Kramer and Smith, 1962; Mraz, Kmiotek, and Frankenberger, 1961; Curtis, 1949). Kramer and Smith related largemouth bass egg survival directly to water temperature during the incubation period. Egg survival was greatest in deeper water because water temperature fluctuations were less, and damage from wind and waves was decreased in deeper water. No eggs survived water temperatures less than 10° C (50° F). The fecundity of the largemouth bass is similar to that of the smallmouth. Individual females produce 5000 to 7000 eggs per pound of fish. Bluegills produce 3000 to 30,000 eggs per individual, depending on size (Brown, 1971).

The white crappie's selection of spawning sites is perhaps even more variable than that of the largemouth bass. Well defined nest depressions are not always constructed, but the substrate simply swept off (Siefert, 1968). Brown (1971) notes the white crappie as building nests in water .91 to 2.5 m (3 to 8 ft) deep, usually near shore. Seifert lists water depths over white crappie nests between .61 and 1.5 m (2 and 4 ft). He also noted that nests tended to be in shallower water when the fish spawned at lower temperatures, presumably to take advantage of warmer daytime temperatures. The normal spawning temperature range is between 17.8° and 21.2° C (64° and 68° F) in California (Curtis, 1949), however, spawning season is exactly the same in Montana, with water temperatures from 14.5° to 21.2° C (58° to 64° F) (Brown, 1971). Siefert (1968) speculates that the spawning period may be more influenced by photoperiod than by temperature. The white crappie adult female generally produces around 15,000 eggs per individual.

The black crappie is closely related to the white crappie and has similar spawning habits. Brown (1971) notes that the black crappie nests in water ranging from 10 cm to 6 m (a few inches to twenty feet) in depth. Fairly soft bottoms, as well as sand and gravel, are used. The preferred temperature range for spawning is between 14.5^{o} and 21.2^{o} C (58^{o} and 64^{o} F) in Montana. Brown states that from 25,000 to 150,000 eggs may be produced by a single female black crappie.

Nests of the black and yellow bullheads are similar in construction to those of the centrarchids. Parental behavior is also similar, except that the adult bullhead guards the fry after they have left the nest. Nests are usually constructed in mud or sand bottoms, with black bullheads nesting in .61 to 1.2 m (2 to 4 ft) of water, and the yellow bullhead in .30 to 1.2 m (1 to 4 ft). Preferred spawning temperatures were not found, but it is known that bullheads spawn at approximately the same time as the channel catfish, whose preferred spawning range is from 23.9^{o} to 26.7^{o} C (75^{o} to 80^{o} F). Black bullhead females produce on the order of 3000 to 8000 eggs, while the fecundity of the yellow bullhead is 1500 to 6500 eggs (Brown, 1971).

Spawning of the channel catfish is unusual. The male selects a site which must be in a dark cavity such as a muskrat burrow, undercut bank, or a crevice in tangled roots or debris (Brown, 1971). Presumably, the depth of water is of minor importance. Water temperature, however, is important and must exceed 23.9^{o} C (75^{o} F) before spawning will commence, with the optimum reported to be around 26.7^{o} C (80^{o} F). The fecundity of the channel catfish is similar to that of the black bullhead, with individual females producing 3000 to 8000 eggs.

Species Which Do Not Build Nests or Redds

Species which do not build nests generally tend to deposit eggs at random over the bottom, although many of these species have decided preferences for bottom type, depth, and velocity of water in which they spawn. Random, or "broadcast" spawners, are usually not overly territorial, nor do they provide parental protection for the eggs or young. Most of these species prefer to lay their eggs in slow, relatively shallow water. However, a few deposit eggs in fairly swift water, which in some cases is quite deep.

Species which select areas of fast water include: sturgeons, paddlefish, longnose dace, white, and longnose suckers, and redhorse.

Little information is available concerning the spawning habits of the sturgeons. Eddy and Surber (1943) report that sturgeons spawn in very swift water, and Brown (1971) notes that they usually spawn over a rocky bottom. Since sturgeons are confined primarily to larger rivers, these areas would be extensive riffle areas within the large rivers. Consequently, study of the spawning habits of sturgeons would be a difficult task, but one which should be done. Sturgeons apparently can neither live nor reproduce in slow or still water, and would thus be greatly affected by reduced discharges.

Considerably more is known about the spawning of the paddlefish, Polyodon spathula. Stockard (1907) noted that the paddlefish spawns only in running water, although it frequently lives in still water. Many others have reported on the long migrations of the paddlefish to its spawning grounds (Elser, 1973; Robinson, 1966). Migration may be the most important aspect of paddlefish spawning. Stockard stated that of the paddlefish he observed, those which had a relatively easy migration appeared to have little trouble spawning. However, many fish arrived at the spawning grounds scratched, bruised, and otherwise injured. These, he speculated, were fish which migrated through shallow water to the spawning ground. Norman Schoenthal, a professor of biology at Eastern Montana College in Billings (personal communication), voiced fears that a lowered spring discharge in the Yellowstone River will expose large areas of shallow sand bars in the vicinity of Garrison Reservoir, North Dakota. Should these areas become too shallow, the fish could become trapped in the lake, and may eventually disappear from the river system because of the loss of reproductive potential. For the paddlefish, the duration of spring runoff may be as important as the magnitude. Fifty to seventy paddlefish are normally caught at Miles City, Montana, during the spawning run, but in 1973, only four were caught. Spring runoff during 1973 reached the average spring crest of the Yellowstone River, but the duration was much shorter. The spawning run at Intake, Montana, about 112 km (70 mi) downstream from Miles City, was about the same as in other years (Allen A. Elser, Montana Dept. of Fish & Game, personal communication, February, 1974). Therefore, it appears that the distance migrated by this species is a function of stage duration for the spring runoff. It is possible that with the falling stage, normally passable bars across the river became impassable, thereby eliminating migration upstream. However, if this were the case, it seems likely that some fish would have been able to reach the spawning grounds, but unable to return. Perhaps there is another cue, as yet unknown, which the paddlefish uses for starting or continuing a migration.

Purkett (1961) stated that migration did not begin until the water temperature had warmed to 10° C (50° F) and there was a rise in water level of one or more meters (several feet). Early season migration required several days of rise in stage to initiate migration, but later migration was initiated by only two or three days of rising stage. Thus, the cue might come from both temperature and water level concurrently, in order for migration to start.

Purkett (1961) states that actual spawning takes place when the water temperature is around 16° C (61° F). Spawning occurs primarily over fairly deep gravel bottoms in rapidly flowing water. The depth at which spawning occurred was reported to be quite variable.

Immediately after fertilization, the eggs acquire a sticky coating which causes them to adhere to the first object they touch. Purkett noted that egg survival was greatest in areas where the eggs adhered singly to pebbles or rocks in a clean swept gravel bar. After hatching, the larvae begin swimming immediately and are usually swept into deeper water. This serves to remove them from the gravel bars before flooding ceases and the bars become exposed.

Robinson (1966) states that the fecundity of the paddlefish is quite high, with individual females producing from 80,000 to 250,000 eggs.

The spawning habits of the longnose sucker are similar to those of the white sucker. Geen, Northcote, Hartman, and Lindsey (1966) state that both species apparently use the same spawning grounds, but that the longnose sucker, Catostomus catostomus, migrates several days earlier than the white sucker, C. commersoni. Olsen and Scidmore (1963) state that their observations of white sucker migrations indicate a homing tendency to a particular spawning site, and a recurring time pattern in the fish movement. Geen, et. al.

(1966) state that longnose suckers begin their migration when the water temperature reaches 5° C (41° F) and that white suckers migrate when water temperatures reach 10° C (50° F). Both species can apparently spawn in fairly small amounts of water. Fertilization and egg deposition is random in swift, shallow water over gravel riffle areas (Reighard, 1920; Geen, et.al., 1966). Geen measured several of the spawning sites and found that the water was generally 15.5 to 31 cm (0.5 to 1.0 ft) in depth, with a velocity of 31 to 46 cm/sec (1.0 to 1.5 ft/sec).

Fecundity for these two species is variable, with individual females producing from 1000 to 100,000 eggs, depending on size. Survival of spawning suckers is very high. To some extent this may be related to absence of aggressive behavior demonstrated by spawners. There is essentially no territoriality demonstrated (Geen, et. al., 1966). The eggs, however, because of their manner of deposition, are subject to a considerable amount of predation by daces and darters (Reighard, 1920).

The longnose dace and the shorthead redhorse (Rhinichthys cataractae and Moxostoma macrolepidotum) are two other species which typically spawn in swift water areas. Migration is apparently limited in the longnose dace, but similar to white, and longnose suckers in the redhorse. Reighard (1920) states that the common redhorse often uses the same spawning sites as the white sucker. Meyer (1962) measured the depth of water over spawning sites for M. macrolepidotum and found that most spawning occurred in .31 to .91 m (1 to 3 ft) of fairly swift water in the main channel of the Des Moines River in Iowa. Spawning of the shorthead, as in most species of redhorse, takes place over a gravel-rubble bottom. Current velocities are probably in the range of 31 to 61 cm/sec (1 to 2 ft/sec), but could be faster. The number of eggs produced by the females is usually between 13,000 and 27,000 per individual.

The spawning sites of the longnose dace are much like the preferred habitat of the dace. Spawning sites are shallow riffle areas over gravel beds, which could mean areas from 5 to 31 cm (several inches to a foot) in depth, with velocities probably in the range of 15.2 to 61 cm/sec (0.5 to 1.5 ft/sec). The fecundity of this species is quite low, with females producing from 400 to 4000 eggs per individual (Brown, 1971).

A great number of species spawn during spring runoff, and although they prefer to spawn in shallow, still water, they are nonetheless dependent, directly or indirectly, on adequate streamflow to attain spawning success.

Among the most notable of these species is the northern pike, *Esox lucius*. The preferred spawning grounds for pike are within shallow, flooded meadows, unually behind a belt of emergent aquatic vegetation. They actively seek suitable spawning areas, preferring a substrate of short vegetation, where the water is warmed by the sun and shading is minimal. The positive reactions of pike to warm water and to the sight of carpets of grass or other plants takes them to the vegetation belt of shallow water. While spawning, pike maintain a constant distance of 5 to 15 cm (2 to 6 in.) above the bottom (Fabricius and Gustafson, 1958). They have been known to spawn in water only 17.8 cm deep (Scott and Crossman, 1973). Pike spawn fairly early in the year, first appearing in nursery areas when water temperatures are between 1.1° and 4.4° C (34° to 40° F) (Franklin and Smith, 1963). However, the males often precede the females by several days, as the females do not migrate until temperatures are around 6.7° C (44° F). The most desirable temperature for egg development is between 8.9° and 11.1° C (48° and 52° F) (Hiner, 1961).

The fecundity of the northern pike may be quite high in larger females. Brown (1971) states that the number of eggs per individual may range between

10,000 and 100,000 depending on the size of the fish. Franklin and Smith (1963) state that under natural conditions, egg survival is unusually high. However, Scott and Crossman (1973) report that egg mortality may occassionally reach 99%. Extreme temperatures, and rapid temperature fluctuation are considered primary causes of egg mortality. Hiner (1961) notes that pike eggs are heavier than those of other species and require rolling in artificial incubation. Therefore, a slightly greater water flow is required for hatching. Velocity should be enough to promote rolling but also low enough to prevent injury to the eggs. However, rolling may be accomplished by wave action or water fluctuations under natural conditions.

Two critical survival periods were identified by the studies of Franklin and Smith (1963). The first is during the embryo stage between fertilization and closure of the blastopore, and the second between hatching and the termination of the alevin stage. They determined that greatest survival of naturally reared fingerlings will result from stabilized high water levels in nursery areas for at least 3 months after egg deposition.

Many cyprinids also spawn in shallow water, but unlike the pike, do not require flooded aquatic or emergent vegetation. Several different species have similar spawning conditions, and they will be generalized where possible. The spawning for many minnows, however, is not known at this time.

Several species spawn in very shallow, still water, and tend to deposit their eggs at random over weedy areas of stream bottom. Among these are the carp, golden shiner, and the northern redbelly dace. The spawning of the carp and the golden shiner is similar, in that egg deposition is random over beds of vegetation. The redbelly dace deposits eggs in masses of filamentous algae (Hubbs and Cooper, 1936; Sigler, 1958).

Carp often spawn in water so shallow that their backs are exposed above the water surface. Sigler (1958) states that the spawning behavior of the carp is extremely animated, even "rowdy", with a great deal of splashing. This behavior is thought to be disturbing to other spawning species, such as the largemouth bass.

The carp spawns when water temperatures range between 14.4° and 16.6° C (58° and 62° F). Egg mortality is likely to be very high, especially when egg deposition occurs in very shallow water which is subject to extreme fluctuations in temperature and depth. The fecundity of the carp is very high, with individual females producing as many as 2,000,000 eggs (Scott and Crossman, 1973).

A large number of species are typically quite random in their choice of spawning sites. Among these are the river carpsucker, largemouth and smallmouth buffalo, emerald shiner, and members of the perch family. Spawning sites for the carpsucker, bigmouth and smallmouth buffalo are in still water along the edges of rivers, over a wide variety of bottom types. Spawning for these three species is probably quite similar to that of the carp.

Johnson (1955) characterizes the spawning behavior of the smallmouth buffalo as a rather noisy, obvious performance involving a great deal of splashing in water about a meter (a few feet) in depth. Brown (1971) describes the spawning of the bigmouth buffalo in similar terms. Spawning starts, for both species, when the water temperature reaches 14.4° C (58° F), but is greatest in the temperature range of 15.5° to 18.3° C (60° to 65° F). Johnson notes that the introduction of fresh water in the pond culture of smallmouth buffalo is necessary for the initiation of spawning. Thus, the stimulus for spawning is probably related to normal spring flooding.

The fecundity of these species can be moderately, to very high. The carpsucker produces around 20,000 to 150,000 eggs per individual, while the bigmouth buffalo may produce as many as 600,000 eggs per individual (Brown, 1971).

The spawning of members of the perch family is somewhat unique. Although the sauger and walleye are known as wide ranging species, and although egg deposition over spawning sites is typically random, there is some evidence that these species may exhibit a tendency to return to a "home" spawning area (Olson and Scidmore, 1962).

Sauger spawning apparently precedes that of the walleye. Nelson (1968) states that peak sauger spawning occurred when the water temperature reached 6.1° C (43° F). Eschmeyer (1950) found that walleye spawning reached its peak at around 8.9° C (48° F).

Hydrologic conditions amenable to the spawning of both sauger and walleye are similar. Eschmeyer found that walleye in the Muskegon River, Michigan, spawned in water 1.5 to 2.5 m (5 to 8 ft.) deep, over a gravel-rubble bottom, with a considerable current. Johnson (1961) states that walleyes usually seek a gravel bottom for the deposition of eggs and that egg survival is highest on a gravel bottom. He also noted that walleyes in the connecting waters of Lake Winnibigoshish, Minnesota, spawned in water from .31 to .91 m (1 to 3 ft) deep. Nelson found that sauger were spawning in water anywhere from .6 to 4.6 m (2 to 15 ft) in depth in the Missouri River. Brown (1971) states that the sauger prefers to spawn in less than five feet of water, but Nelson states that the greatest egg survival occurred in eggs which were always covered by at least 1.2 m (4 ft) of water. It is possible that current velocity has some effect on the preferred depth of water in both walleye and sauger. Eschmeyer noted that walleyes spawning in lakes often lay their eggs in water less than .91 m (3 ft) deep, which corroborates with what Johnson found in the slow flowing channels he studied. Since the members of this genus obviously show a wide range in depths, perhaps egg survival should be used to determine optimum hydrologic conditions for spawning. These conditions could probably be defined as water areas greater than 1.2 m (4 ft) in depth with gravel bottoms and with moderate velocities.

Herman, et. al. (1959) states that the spawning of the yellow perch closely follows that of the walleye. The yellow perch is less particular about its spawning substrate than either the walleye or sauger, and normally deposits its eggs in water greater than 1.5 m (5 ft) in depth.

The fecundity of the yellow perch is slightly lower than that of the walleye and sauger. Individual yellow perch usually deposit from 10,000 to 40,000 eggs, while the average number of eggs for walleye and sauger is around 50,000 per individual (Brown, 1971).

GLOSSARY

Aggradation: Sedimentation within a stream channel resulting in a rise in elevation of the stream bottom.

Allochthonous: Organic material originating from areas outside the confines of the stream channel, and falling into the stream.

Anchor Ice: Ice which forms on stream bottoms during cold weather.

Autochthonous: Organic material such as algae, which originates within the confines of the stream channel.

Benthos: Refers to aquatic invertebrates such as molluscs, immature aquatic insects, crustaceans, etc., which live on or within the stream bottom.

Biocoenoce: An ecological unit comparable to the community, which is delineated primarily by similarity of ecological conditions.

Crepuscular: Becoming active at twilight or just before sunrise.

Degradation: The process of downcutting within a stream channel which results in a lowering of the elevation of the stream bed.

Drift: Refers to aquatic invertebrates which have released from, or have been swept from the substrate, and float with the current.

Falcate: Shaped or curved like a crescent.

Hydraulic geometry: Refers to flowing water parameters such as depth, width, velocity, and load, and their relation to discharge.

Hydraulic gradient: Slope of the surface of the water table.

Hydrologic regime: Climatic, lithographic, topographic, and vegetation factors, and the temporal distribution of seasonally variable factors, which lead to a given equilibrium condition between a stream and its drainage basin.

Hydrophyte: A plant which requires a perennial source of surface water, or very shallow groundwater.

Interspecific competition: Competition between two or more different species.

Intraspecific competition: Competition between two or more individuals of the same species.

Laminar flow: Smooth, low velocity flow, with parallel layers of water shearing over one another, and with no mixing of layers.

Permeability: Ability of an aquifer to transmit water; also, rate of flow through a unit area of aquifer face at unit hydraulic gradient.

Phreatophyte: A plant which habitually obtains its water supply from ground water, either directly or from the capillary fringe...

Piscivore: Any animal whose primary food source is fish.

Recharge: The process of replenishing ground water supply.

Redd: A shallow trench or hole excavated in a stream bottom during spawning, in which eggs are laid and fertilized, and which is usually covered over during incubation.

Sediment capacity: Refers to the quantity of sediment which can be moved by a river at a given discharge.

Sediment competence: Refers to the size of sediment particles which can be moved by a river at a given discharge.

Soft-rayed: Refers to fish species which do not have sharp spines on dorsal or pectoral fins.

Specific yield: Amount of water released against the force of gravity by an aquifer. Numerically, the volume of water released per unit area by a unit decrease in depth of ground water.

Succession: A process by which one species or group of species modifies a habitat to the extent that it becomes favorable for the invasion by other species, to the eventual replacement of the original species.

Transmissivity: Amount of water released by an aquifer, measured from a strip of unit width over the thickness of the aquifer.

Trophic level: Refers to the position occupied by an organism in a simplified food chain.

Turbulent flow: Flow with secondary, heterogeneous eddies superimposed on the main forward flow, with considerable mixing of components.

Waste assimilation capacity: The amount of organic waste which can be added to a body of water without significant deterioration of water quality.

REFERENCES

1. Ali, M.A., and Anctil, M. 1968. "Relationship Between Retinal Structure and Habitat of *Stizostedion vitreum vitreum* & *S. canadense*," *Journal of the Fisheries Research Board of Canada*, 25 (9): 2001-2003.

2. Alonso, C.V., McHenry, J.R., and Hong, J-C.S. 1973. "The Influence of Suspended Sediment on the Surface Reaeration of Uniform Streams," Water Resources Research Institute, Mississippi State University, 50 pp.

3. Anderson, Richard O. 1973. "Application of Theory and Research to Management of Warm-Water Fish Populations," *Transactions of the American Fisheries Society*, 102 (1): 164-171.

4. Bailey, Reeve M. 1955. "Differential Mortality from High Temperature in a Mixed Population of Fishes in Southern Michigan," *Ecology*, 36 (3): 526-528.

5. ----------------and Cross, Frank B. 1954. "River Sturgeons of the Genus *Scaphirhynchus*: Characteristics, Distribution, and Synonymy," Michigan Academy of Science, Arts, & Letters, 39: 169-208.

6. Bardach, John E. and Bjorklund, Richard. 1957. "The Temperature Sensitivity of Some North American Freshwater Fishes," *American Naturalist*, 91 (859): 233-251.

7. Beckman, W.C. 1941. "Increased Growth Rate of Rock Bass, *Ambloplites rupestris* (Rafinesque) Following Reduction in the Density of the Population," *Transactions of the American Fisheries Society*, 70: 143-148.

8. Bennett, G.W. 1944. "The Effect of Species Combinations on Fish Production," *Transactions of the North American Wildlife Conference*, 9: 184-188.

9. Beyerle, George B. and Williams, John E. 1968. "Some Observations of Food Selectivity by Northern Pike in Aquaria," *Transactions of the American Fisheries Society*, 97 (1): 28-30.

10. Bishop, Robert A. and Scott, James W. 1973. "The Determination and Establishment of Minimum Stream Flows in Washington State," Washington State Department of Ecology, Olympia, *Draft Report No. 73-033*, 81 pp.

11. Bjorn, Eugene E. 1940. "Preliminary Observations and Experimental Study of the Ling, *Lota inasculosa* (LeSueur) in Wyoming," *Transactions of the American Fisheries Society*, 69: 192-196.

12. Bonde, Tomas and Maloney, J.E. 1960. "Food Habits of Burbot," *Transactions of the American Fisheries Society*, 89 (4): 374-376.

13. Boussu, Marvin F. 1954. "The Relationship Between Trout Populations and Cover on a Small Stream," Journal of Wildlife Management, 18 (2): 229-239

14. Bovee, K.D., Gagenmeier, G., McBride, J., Sosebee, J., and Sully, M. 1973. "A Mathematical Model for the Prediction of Dissolved Oxygen in the Clark Fork River Below Missoula, Montana," Student Environmental Research Center, University of Montana, Research Report #10, 41 pp.

15. Bovee, Ken D. 1973 "Some Qualitative Effects on Surface Hydrology of Coal Development in Eastern Montana," Research Report #9, Student Environmental Research Center, University of Montana, 15 pp.

16. Bowie, James E. and Kam, William. 1968 "Use of Water by Riparian Vegetation, Cottonwood Wash, Arizona," U.S.G.S. Water Supply Paper No. 1858. 62 pp.

17. Brown, C.J.D. 1971. Fishes of Montana, Big Sky Books, Montana State University, Bozeman, 207 pp.

18. ------------, Clothier, W.D., and Alvord, W. 1953. "Observations on Ice Conditions and Bottom Organisms in the West Gallatin River, Montana," Proceedings of the Montana Academy of Science, 13: 21-27.

19. Burkham, D.E. 1972. "Channel Changes of the Gila River in Safford Valley, Arizona, 1846-1970," U.S.G.S. Professional Paper 655-G, 24 pp.

20. ------------ 1970. "A Method for Relating Infiltration Rates to Streamflow Rates in Perched Streams," U.S.G.S. Professional Paper 700-D, D266-D271.

21. Burton, G.W. and Odum, E.P. 1945. "The Distribution of Stream Fish in the Vicinity of Mountain Lake, Virginia," Ecology, 26: 182-194.

22. Buscemi, Philip A. 1966. "The Importance of Sedimentary Organics in the Distribution of Benthic Organisms" In: Organism-Substrate Relationships in Streams. Special Publication #4, Pymatuning Laboratory of Ecology, University of Pittsburgh. pp. 79-86.

23. Cahn, Alvin R. 1929. "The Effect of Carp on a Small Lake: The Carp as a Dominant," Ecology, 10: 271-274.

24. ------------- 1936. "Observations on the Breeding of the Lawyer, Lota maculosa," Copeia (3): 163-165.

25. Cairns, John and Dickson, K.L., "An Ecosystematic Study of the South River, Virginia," Virginia Polytechnic Institute Water Resources Research Center, Bulletin #54, July 1972, 104 pp.

26. Campbell, C.J. and Green, W. 1968. "Perpetual Succession of Stream Channel Vegetation in a Semi-Arid Region," Journal of the Arizona Academy of Science, 5 (2): 86-98.

27. Carbine, W.F. 1939. "Minnows (Cyprinidae)," Institute of Fisheries Research, Michigan Department of Conservation, Report #528, pp. 1-12.

28. Carlson, Dale R. 1967. "Fathead Minnow (Pinephales promelas) in the Des Moines River, Boone County, Iowa, and the Skunk River Drainage, Hamilton and Story Counties, Iowa," Iowa State Journal of Science, 41 (3): 363-374.

29. Chapman, D.W. 1966a. "Food and Space as Regulators of Salmonid Populations in Streams," American Naturalist, 100 (913): 345-357.

30. ------------ 1966b. "The Relative Contributions of Aquatic and Terrestrial Primary Producers to the Trophic Relations of Stream Organisms" In: Organism-Substrate Relationships in Streams. Special Publication #4, Pymatuning Laboratory of Ecology, University of Pittsburgh. pp. 116-130.

31. Chen, Lo-Chai. 1969. "The Biology and Taxonomy of the Burbot, Lota lota leptura, in Interior Alaska," University of Alaska, Biological Papers, 11: 53 pp.

32. Clay, Wm. 1962. Kentucky Fishes. Kentucky Department of Fish & Wildlife Resources. 147 pp.

33. Coffin, Donald L. 1968. "Relation of Channel Width to Vertical Permeability of Streambed in Big Sandy Creek, Colorado," U.S.G.S. Professional Paper 600-B, pp. B215-B218.

34. Coker, R.E. 1930. "Studies of the Common Fishes of the Mississippi River at Keokuk," Bulletin of the Bureau of Fisheries, U.S. Fish & Wildlife Service, 45: 141-225.

35. Collier, B.D., Cox, G.W., Johnson, A.W. and Miller, P.C. 1973. Dynamic Ecology, Prentice Hall, Englewood, New Jersey, 563 pp.

36. Collings, M.R., Smith, Ronald W. and Higgins, G.T. 1972. "The Hydrology of Four Streams in Western Washington as Related to Several Pacific Salmon Species," U.S.G.S. Water Supply Paper, 1968, 109 pp.

37. Cordone, A.J. and Kelley, D.W. 1961. "The Influence of Inorganic Sediment on the Aquatic Life of Streams," California Fish & Game, 47: 189-228.

38. Cummins, Kenneth W. 1966. "A Review of Stream Ecology With Special Emphasis on Organism-Substrate Relationships" In: Organism-Substrate Relationships in Streams. Special Publication #4, Pymatuning Laboratory of Ecology, University of Pittsburgh. pp. 2-51.

39. Curry, Robert. 1972. "Rivers - A Geomorphic and Chemical Overview," In: River Ecology and Man, Academic Press, Inc. New York, pp. 9-31.

40. Curtis, Brian. 1959. "Changes in a River's Physical Characteristics Under Substantial Reductions in Flow Due to Hydroelectric Diversion," California Fish & Game, 45 (3): 181-188.

41. -------------- 1949. "The Warm-Water Game Fishes of California," California Fish & Game, 35 (3): 255-274.

42. Cushing, Colbert E. 1963. "Filter Feeding Insect Distribution and Planktonic Good in the Montreal River," Transactions of the American Fisheries Society, 92 (3): 216-219.

43. Davidson, F.A., Vaughn, Elizabeth, Hutchinson, S.J. and Pritchard, A.L. 1943. "Factors Influencing the Upstream Migration of the Pink Salmon (Oncorhynchus corbuscha)," Ecology, 24 (2): 149-168.

44. Dimond, John B. 1967. "Evidence that Drift of Stream Benthos is Density Related," Ecology, 48 (5): 855-857.

45. Doudoroff, Peter and Shumway, Dean L. 1967. "Dissolved Oxygen Criteria for the Protection of Fish" In: A Symposium on Water Quality Criteria to Protect Aquatic Life. American Fisheries Society, Special Publication #4, pp. 13-19.

46. Eddy, Samuel and Surber, Thaddeus. 1943. "Northern Fishes," University of Minnesota Press, Minneapolis, 276 pp.

47. Edington, J.M. 1968. "Habitat Preferences in Net-Spinning Caddis Larvae," Journal of Animal Ecology, 37 (3): 675-692.

48. Egglishaw, H.J. 1964. "The Distributional Relationship Between the Bottom Fauna and Plant Detritus in Streams," Journal of Animal Ecology, 33: 463-476.

49. Elliot, J.M. 1967. "Invertebrate Drift in a Dartmoor Stream," Archives of Hydrobiology, 63 (2): 202-237.

50. ----------- 1971. "Life Histories and Drifting of Three Species of Limnephilidae (Trichoptera)," Oikos, 22 (1): 56-61.

51. ----------- 1968. "Life Histories and Drifting of Trichoptera in a Dartmoor Stream," Journal of Animal Ecology, 37: 615-625.

52. Elliott, J.M. 1973. "The Food of Brown and Rainbow Trout (S. trutta and S. gairdnerii) in Relation to the Abundance of Drifting Invertebrates in a Mountain Stream," Oecologia (Berl.) 12 (4): 329-347.

53. Elser, Allen A. 1972. "A Partial Evaluation and Application of the 'Montana Method' of Determining Stream Flow Requirements" In: *Proceedings of the Instream Flow Requirement Workshop*, Portland, Oregon, March 15-16, 1972, pp. 3-8.

54. ------------ 1973. "Southeast Montana Fisheries Investigation," Montana Department of Fish & Game, *Job Progress Report*, Project F-30-R-8, Job I-b, 14 pp.

55. Emmett, W.W. 1965. "The Vigil Network: Methods of Measurement and a Sampling of Data Collected," Symposium of Budapest, *International Association of the Science of Hydrology Publication*, 66: 89-106.

56. Eschmeyer, Paul H. 1950. "The Life History of the Walleye, *Stizostedion vitrium*, in Michigan," *Bulletin of the Institute of Fisheries Research*, Michigan Department of Conservation, 3: 99 pp.

57. Fabricius, E. 1951. "The Topography of the Spawning Bottom as a Factor Influencing the Size of the Territory in Some Species of Fish," *Report of the Institute of Freshwater Research*, Drottningholm, Sweden, 32: 43-49.

58. ------------ and Gustafson, K.J. 1958. "Some New Observations on the Spawning Behavior of the Pike, *Esox lucius*," *Report of the Institute of Freshwater Research*, Drottningholm, Sweden, 39: 23-54.

59. Fajen, Otto F. 1962. "The Influence of Stream Stability on Homing Behavior of Two Smallmouth Bass Populations," *Transactions of the American Fisheries Society*, 91 (4): 346-349.

60. Forbes, S.A. 1907. "On the Local Distribution of Certain Illinois Fishes; An Essay in Statistical Ecology," *Bulletin of the Illinois State Laboratory of Natural History*, 7: 273-303.

61. Franklin, Donald R. and Smith, Lloyd L, Jr. 1963. "Early Life History of the Northern Pike, *Esox lucius*, With Special Reference to the Factors Influencing the Numerical Strength of the Year Class," *Transactions of the American Fisheries Society*, 92 (2): 91-110.

62. Fraser, J.C. 1971. "Regulated Discharge and the Stream Environment," International Symposium on River Ecology and the Impact of Man, June 20-23, 1971, University of Massachusetts at Amherst, 41 pp.

63. Gaufin, Arden and Hern, Stephen. 1971. "Laboratory Studies on Tolerance of Aquatic Insects to Heated Waters," *Journal of the Kansas Entomological Society*, 44 (2): 240-245.

64. Gee, J.H. and Northcote, T.G. 1963. "Comparative Ecology of Two Sympatric Species of Dace (*Rhinicthys*) in the Fraser River System, B.C.," *Journal of the Fisheries Research Board of Canada*, 20 (1): 105-118.

65. Geen, G.H., Northcote, T.G., Hartman, G.F., and Lindsey, C.C. 1966. "Life Histories of Two Species of Catostomid Fishes in Sixteen Mile Lake, B.C.; With Specific Reference to Inlet Stream Spawning," Journal of the Fisheries Research Board of Canada, 23 (11): 1761-1788.

66. Gerking, S.D. 1953. "Evidence for the Concepts of Home Range and Territory in Stream Fishes," Ecology, 34: 347-365.

67. ------------ 1950. "Stability of a Stream Fish Population," Journal of Wildlife Management, 14: 193-202.

68. Gibbs, Phil. 1971. "Remarks Concerning the Montana-Wyoming Aqueduct Study," Bureau of Reclamation, Region 6, Billings, Montana, Nov. 19, 1971.

69. Giger, Richard D. 1973. "Streamflow Requirements for Salmonids," Oregon Wildlife Commission, Job Final Report, Project AFS 62-1, 117 pp.

70. Gunderson, Donald R. 1966. "Stream Morphology and Fish Populations in Relation to Floodplain Use," M.S. Thesis, Montana State University, Bozeman, Montana.

71. Haines, Terry A. 1973. "Effects of Nutrient Enrichment and a Rough Fish Population (Carp) on a Game Fish Population (Smallmouth Bass)," Transactions of the American Fisheries Society, 102 (2); 346-354.

72. ---------------- and Butler, R.L. 1969. "Responses of Yearling Smallmouth Bass (M. dolomieni) to Artificial Shelter in a Stream Aquarium," Journal of the Fisheries Research Board of Canada, 26 (1): 21-31.

73. Hallam, J.C. 1959. "Habitat and Associated Fauna of Four Species of Fish in Ontario Streams," Journal of the Fisheries Research Board of Canada, 16: 147-173.

74. Hasler, A.D. and Wisby, W.J. 1958. "The Return of Displaced Largemouth Bass and Green Sunfish to a 'Home' Area," Ecology, 39: 289-293.

75. Hayes, F.R. 1953. "Artificial Freshets and Other Factors Controlling the Ascent and Population of Atlantic Salmon in the La Have River, Nova Scotia," Bulletin of the Fisheries Research Board of Canada, 99: 1-47.

76. Herman, Elmer, Wisby, Warren, Wiegert, Lawrence and Burdick, Milton. 1959. "The Yellow Perch; Its Life History, Ecology, and Management," Wisconsin Conservation Department Publication, 228: 1-14.

77. Hiner, Laurence E. 1961. "Propagation of Northern Pike," Transactions of the American Fisheries Society, 90 (30): 298-302.

78. Hooper, Douglas R. 1973. "Evaluation of the Effects of Flows on Trout Stream Ecology," Pacific Gas and Electric Company, Department of Engineering Research, Emeryville, California, 97pp.

79. Hosner, John F. 1958. "The Effects of Complete Inundation Upon Seedlings of Six Bottomland Tree Species," Ecology 39 (2): 371-373.

80. Hubbs, Carl L. 1941. "The Relation of Hydrological Conditions to Speciation in Fishes" In: A Symposium on Hydrobiology, University of Wisconsin, pp. 182-195.

81. --------------and Bailey, Reeve M. 1938. "The Smallmouthed Bass," Cranbrook Institute of Science, Bloomfield Hills, Michigan, *Bulletin #10*, 89 pp.

82. -------------and Cooper, Gerald P. 1936. "Minnows of Michigan," Cranbrook Institute of Science, Bloomfield Hills, Michigan, *Bulletin #8*, 95 pp.

83. Huet, Marcel. 1959. "Profiles and Biology of Western European Steams as Related to Fish Management," *Transactions of the American Fisheries Society*, 88 (3): 155-163.

84. Hynes, H.B.N. 1970. "The Ecology of Flowing Waters in Relation to Management," *Journal Water Pollution Control Federation*, 42 (3)I: 418-424.

85. ------------ 1958. "The Effect of Drought on the Fauna of a Small Mountain Stream in Wales," *Verh. Internat. Ver. Limnol.* XIII, Stuttgart.

86. ------------ 1972. *The Ecology of Running Water*, University of Toronto Press, 555 pp.

87. Johnson, Fritz H. 1961. "Walleye Egg Survival During Incubation on Several Types of Bottom in Lake Winnibigoshish, Minnesota, and Connecting Waters," *Transactions of the American Fisheries Society*, 90 (3): 312-322.

88. Johnson, Leon D. 1969. "Food of Angler-Caught Northern Pike in Murphy Flowage," Wisconsin Department of Natural Resources *Technical Bulletin # 42*. 26 pp.

89. Johnson, Murray G. 1965. "Estimates of Fish Populations in Warm-Water Streams by the Removal Method," *Transactions of the American Fisheries Society*, 94 (4): 350-357.

90. Johnson, R.P. 1955. "Studies on the Life History and Ecology of the Bigmouth Buffalo, *Ictiobus cyprinellus*," *Journal of the Fisheries Research Board of Canada*, 20: 1397-1429.

91. Kennedy, Harry D. 1967. "Seasonal Abundance of Aquatic Invertebrates and their Utilization by Hatchery Reared Rainbow Trout," U.S. Bureau of Sport Fisheries and Wildlife, *Technical Paper #12*, 41 pp.

92. Kraft, Melvin E. 1968. "The Effects of Controlled Dewatering on a Trout Stream," M.S. thesis, Montana State University, Bozeman.

93. ---------------- 1972. "Effects of Controlled Flow Reduction on a Trout Stream," *Journal of the Fisheries Research Board of Canada*, 29: 1405-1411.

94. Kramer, Robert H. and Smith, Lloyd L. 1962. "Formation of Year Classes in Largemouth Bass," Transactions of the American Fisheries Society, 91 (1): 29-41.

95. Krumbein, W.C. and Sloss, L.L. 1955. Stratigraphy and Sedimentation. W.H. Freeman Co., San Francisco. 497 pp.

96. Krumholtz, Louis A., Charles, J.R., and Minckley, W.L. 1962. "The Fish Population of the Ohio River," In: Aquatic Life Resources of the Ohio River, Ohio River Valley Water Sanitation Commission, pp. 51-89.

97. Kuehne, R.A. 1962. "A Classification of Streams Illustrated by Fish Distribution in an Eastern Kentucky Creek," Ecology, 43: 608-614.

98. Langbein, W.B. and Schumm, S.A. 1958. "Yield of Sediment in Relation to Mean Annual Precipitation," Trans. Am. Geophysical Union, 39: 1076-1084.

99. Larimore, R.W. 1954. "Dispersal, Growth, and Influence of Smallmouth Bass Stocked in a Warm-Water Stream," Journal of Wildlife Management, 18: 207-216.

100. -----------, Childers, W.F., and Heckrotte, C. 1959. "Destruction and Re-establishment of Stream Fish and Invertebrates Affected by Drought," Transactions of the American Fisheries Society, 88: 261-285.

101. ------------, and Smith, Philip W. 1963. "The Fishes of Champaign County, Illinois, as Affected by 60 Years of Stream Changes," Illinois Natural History Survey Bulletin, 28 (2): 299-382.

102. Larkin, P.A. 1956. "Interspecific Competition and Population Control in Freshwater Fish," Journal of the Fisheries Research Board of Canada, 13: 327-342.

103. Leopold, Luna B. 1962. "Rivers," American Scientist, 50 (4): 511-537.

104. --------------, Wolman, M. Gordon, and Miller, John P. 1964. Fluvial Processes in Geomorphology, W.H. Freeman and Company, 522 pp.

105. Lewis, Stephen L. 1969. "Physical Factors Influencing Fish Populations in Pools," M.S. thesis, Montana State University, Bozeman.

106. Logan, Sidney M. 1963. "Winter Observations of Bottom Organisms and Trout in Bridger Creek, Montana," Transactions of the American Fisheries Society, 92 (2): 140-145.

107. Macan, T.T. 1963. Freshwater Ecology, Longmans, Green & Co., Ltd., London, 348 pp.

108. Maciolek, John and Needham, P.R. 1951. "Ecological Effects of Winter Conditions on Trout and Trout Foods in Convict Creek, California," Transactions of the American Fisheries Society, 81: 202-217.

109. Meinzer, Oscar E. 1927. "Plants as Indicators of Ground Watre," U.S. Geological Survey Water Supply Paper #577, 95 pp.

110. Meyer, W.H. 1962. "Life History of Three Species of Redhorse (Moxostoma) in the Des Moines River, Iowa," Transactions of the American Fisheries Society, 91: 412-419.

111. Milhous, Robert T.1973. "A Review of Fisheries Minimum Flow Methodologies from the Viewpoint of Water Availability," Presented at the 1973 National Conference of the American Water Resources Association, Seattle, Washington, October 22-24, 1973.

112. Mills, Harlow B., Starrett, W.C., and Bellrose, F.C. 1966. "Man's Effect on the Fish and Wildlife of the Illinois River," Illinois Natural History Survey, Biological Notes, 57: 1-24.

113. Minckley, W.L. 1963. "The Ecology of a Spring Stream, Doe Run, Meade County, Kentucky," Wildlife Monographs, 11: 1-124.

114. Minshall, G. Wayne and Winger, Parley V. 1968. "The Effect of Reduction in Stream Flow on Invertebrate Drift," Ecology, 49 (3): 580-582.

115. Morisawa, Marie. 1968. Streams: their dynamics and morphology, McGraw-Hill Book Company, 175 pp.

116. Moss, D.D. and Scott, D.C. 1961. "Dissolved Oxygen Requirements of Three Species of Fish," Transactions of the American Fisheries Society, 90 (4): 377-393.

117. Mraz, Donald, Kmiotek, Stanley, and Frankenberger, Ludwig. 1961. The Largemouth Bass-Its Life History, Ecology, and Management, Wisconsin Conservation Department Publication #232. 15 pp.

118. Needham, P.R. and Jones, A.C. 1959. "Flow, Temperature, Solar Radiation and Ice in Relation to Activites of Fishes in Sagehen Creek, California," Ecology, 40: 465-474.

119. -----------, and Usinger, Robert L. 1956. "Variability in the Macrofauna of a Single Riffle in Prosser Creek, California, as Indicated by Surber Sampler," Hilgardia, 24 (4): 383-409.

120. Nelson, W.R. 1968. "Reproduction and Early LIfe History of Sauger (Stizostedion canadense) in Lewis and Clark Lake," Transactions of the American Fisheries Society, 97 (2): 159-166.

121. O'Conner, D.J. and Dobbins, W.E. 1958. "Mechanisms of Reaeration in Natural Streams," Transactions of the American Society of Civil Engineers, 123:

122. Odum, H.T. 1957. "Trophic Structure and Productivity of Silver Springs, Florida," Ecological Monographs, 27: 55-112.

123. Olson, D.E. 1963. "Role of the White Sucker in Minnesota Waters," Proceedings of the Minnesota Academy of Science, 31: 68-73.

124. -----------and Scidmore, Warren J. 1962. "Homing Behavior of Spawning Walleyes," Transactions of the American Fisheries Society, 91 (4): 355-361.

125. -----------and-------------. 1963. "Homing Tendency of Spawning White Suckers in Many Point Lake, Minnesota," Transactions of the American Fisheries Society, 92 (1): 13-16.

126. Parsons, John W. 1959. "Muskellunge in Tennessee Streams," Transactions of the American Fisheries Society, 88 (2): 136-140.

127. Pearson, W.D. and Franklin, D.R. 1968. "Some Factors Affecting Drift of *Baetis* and Simuliidae in a Large River," Ecology, 49 (1): 75-81.

128. ------------- and Kramer, R.H. 1972. "Drift and Production of Two Aquatic Insects in a Mountain Stream," Ecological Monographs, 24 (3): 365-385.

129. Percival, E. and Whitehead, H. 1929. "A Quantitative Study of the Fauna of Some Types of Streambed," Journal of Ecology, 17: 282-314.

130. Peters, J.C. 1967. "Effects on a Trout Stream of Sediment from Agricultural Practises," Journal of Wildlife Management, 31 (4): 805-812.

131. Peterson, D.E. and Jaske, R.T. 1970. Simulation Modeling of Thermal Effluent, Battelle Memorial Institute, Pacific Northwest Laboratories, AEC Research and Development Report # BNWL-1277. 21 pp.

132. Prescott, G.W. 1968. The Algae: A Review, Houghton Mifflin Company, Boston, 436 pp.

133. Proceedings of the Instream Flow Requirement Workshop, March 15-16, 1972, Portland Oregon. Pacific Northwest River Basins Commission, 85 pp.

134. Purkett, C.A. 1961. "Reproduction and Early Development of the Paddlefish," Transactions of the American Fisheries Society, 87: 116-131.

135. Reighard, Jacob. 1920. "The Breeding Behavior of the Suckers and Minnows," Biological Bulletin, 38: 1-32.

136. Reimers, Norman. 1963. "Body Condition, Water Temperature, and Overwinter Survival of Hatchery Reared Trout in Convict Creek, California," Transactions of the American Fisheries Society, 92 (1): 39-46.

137. Reynolds, J.B. 1965. "Life History of Smallmouth Bass, *Micropterus dolomieu* (Lacepede), in the Des Moines River, Boone County, Iowa," Iowa State College Journal of Science, 39: 417-436.

138. Ricker, W.F. and Gottschalk, J. 1941. "An Experiment in Removing Coarse Fish from a Lake," *Transactions of the American Fisheries Society*, 70: 382-390.

139. Riley, G.F. 1953. "Theory of Growth and Competition in Natural Populations," *Journal of the Fisheries Research Board of Canada*, 10 (5): 211-223.

140. Robinson, John W. 1966. "Observations on the Life History, Movement, and Harvest of the Paddlefish (*Polyodon spathula*) in Montana," *Proceedings of the Montana Academy of Science*, 26: 33-44.

141. Robinson, T.W. 1952. "Phreatophytes and Their Relation to Water in Western States." *Transactions of the American Geophysical Union*, 33 (1): 57-61

142. -----------. 1956. "Phreatophytes," Ground Water Short Course, Baton Rouge, Louisiana, February 10, 1956, 25 pp.

143. Sams, R.E. and Pearson, L.S. 1963. "Methods for Determining Spawning Flows for Anadromous Salmonids," Oregon Fish Commission, unpublished manuscript. with permission of authors. 67 pp.

144. Scott, D. 1958. "Ecological Studies of the Trichoptera of the River Dean, Cheshire." *Archiv. Hydrobiol.*, 54: 340-392.

145. ----------. 1949. "A Study of a Stream Population of Rock Bass, *Amblo-plites rupestris*," *Investigations of Indiana Lakes and Streams*, 3: 169-234.

146. ----------. 1966. "The Substrate Cover-Fraction Concept," In: *Organism-Substrate Relationships in Streams*, Special Publication #4, Pymatuning Laboratory of Ecology, University of Pittsburgh, pp. 75-78.

147. Scott, W.B. and Crossman, E.J. 1973. Freshwater Fishes of Canada. Fisheries Research Board of Canada, Bulletin 184: 966 pp.

148. Sheldon, A.L. 1968. "Species Diversity & Longitudinal Succession in Stream Fishes," *Ecology*, 49 (2): 193-198.

149. ------------. 1974. Class notes. Zoology 360, Community Ecology, Spring Quarter, 1974. University of Montana, Missoula.

150. Shelford, V.E. 1911. "Ecological Succession. I. Stream Fishes and the Method of Physiographic Analysis," *Biological Bulletin*, 21: 9-34.

151. Siefert, Richard E. 1968. "Reproductive Behavior, Incubation, and Mortality of Eggs, and Postlarval Food Selection in the White Crappie," *Transactions of the American Fisheries Society*, 97 (3): 252-259.

152. Sigler, W.F. 1958. "The Ecology and Use of Carp in Utah," *Utah State University Bulletin*, 405: 1-63

153. Silver, Stuart, Warren, Charles E., and Doudoroff, Peter. 1963. "Dissolved Oxygen Requirements of Developing Steelhead Trout and Chinook Salmon Embryos at Different Water Velocities," Transactions of the American Fisheries Society, 92 (4): 327-343.

154. Simco, W.A. and Cross, F.B. 1966. "Factors Affecting Growth and Production of Channel Catfish, Ictalurus punctatus," University of Kansas Publications, Museum of Natural History, 17 (4): 191-256.

155. Sprules, W.M. 1947. "An Ecological Investigation of Stream Insects in Algonquin Park, Ontario," University of Toronto Studies, Biol. 56, Publications of the Ontario Fisheries Research Laboratory, 69: 1-81.

156. Starrett, W.C. 1950a. "Distribution of the Fishes of Boone County, Iowa, with Special Reference to the Minnows and Darters," American Midland Naturalist, 43: 112-127.

157. ------------. 1950b. "Food Relationships of the Minnows of the Des Moines River, Iowa," Ecology, 31: 216-233.

158. Stockard, C.R. 1907. "Observations on the Natural History of Polyodon spathula," American Naturalist, 41: 753-766.

159. Stroud, Richard H. 1967. "Water Quality Criteria to Protect Aquatic Life: A Summary," In: A Symposium on Water Quality Criteria to Protect Aquatic Life, American Fisheries Society Special Publication #4: 33-37.

160. Summerfelt, R.C. and Minckley, C.O. 1969. "Aspects of the Life History of the Sand Shiner, Notropis stramineus (Cope), in the Smoky Hill River, Kansas," Transactions of the American Fisheries Society, 98 (3): 444-453.

161. Tennant, Donald L. 1972. "A Method for Determining Instream Flow Requirements for Fish, Wildlife, and the Aquatic Environment," Proceedings, Instream Flow Requirement Workshop, Pacific Northwest River Basins Commission, Vancouver, Washington, pp. 3-11.

162. Tester, A.L. 1931. "Spawning Habits of the Small-mouth Black Bass in Ontario Waters," Transactions of the American Fisheries Society, 60: 53-61.

163. Thompson, D.H. 1925. "Some Observations on the Oxygen Requirements of Fishes in the Illinois River," Illinois Natural History Survey, 25 (7): 423-437.

164. -----------and F. Hunt. 1930. "The Fishes of Champaign County," Illinois Natural History Survey Bulletin, 19 (1): 101 pp.

165. Thompson, Ken. 1972. "Determining Stream Flows for Fish Life," In: Proceedings of the Instream Flow Requirement Workshop, Portland, Oregon, March 15-16, 1972, pp. 31-46.

166. Thorup, Jens. 1966. "Substrate type and its Value as a Basis for the Delimitation of Bottom Fauna Communities in Running Water," In: *Organism-Substrate Relationships in Streams, Special Publication #4*, Pymatuning Laboratory of Ecology, University of Pittsburgh, pp. 59-74.

167. Trautman, M.B. 1942. "Fish Distribution and Abundance Correlated with Stream Gradients as a Consideration in Stocking Programs," *Transactions 7th North American Wildlife Conference*, pp. 211-233.

168. Tubb, Richard A., F.A. Copes, C. Johnston. 1965. "Fishes of the Sheyenne River of North Dakota," *Proceedings of the North Dakota Academy of Science*, 19: 120-128.

169. Van Oosten, J. 1944. "Factors Affecting the Growth of Fish," *Transactions 9th North American Wildlife Conference*, 9: 177-183.

170. Vaux, Walter G. 1968. "Intergravel Flow and Interchange of Water in a Streambed," U.S. Fish and Wildlife Service, *Fishery Bulletin*, 66 (3): 479-489.

171. Velz, Clarence. 1970. *Applied Stream Sanitation*, John Wiley & Sons, New York, 619 pp.

172. Waters, Thomas F. 1961. "Standing Crop and Drift of Stream Bottom Organisms," *Ecology*, 42 (3): 532-537.

173. ------------. 1962. "A Method to Estimate the Production Rate of a Stream Bottom Invertebrate," *Transactions of the American Fisheries Society*, 91 (3): 243-250.

174. ------------. 1965. "Interpretation of Invertebrate Drift in Streams," *Ecology*, 46: 327-334.

175. Weeks, E.P. and Sorey, M.L. 1973. "Use of Finite Difference Arrays of Observation Wells to Estimate Evapotranspiration from Ground Water in the Arkansas River Valley, Colorado," *U.S. Geological Survey Water Supply Paper #2029-C*.

176. Welker, Bill D. 1967. "Comparison of Channel Catfish Populations in Channeled and Unchanneled Sections of the Little Sioux River, Iowa," *Proceedings of the Iowa Academy of Science*, 74: 99-104.

177. Wene, G. and Wickliff, E.L. 1940. "Modification of a Stream Bottom and its Effect on the Insect Fauna," *Canadian Entomologist*, 72: 131-135.

178. Wesche, Thomas A. 1973. "Parametric Determination of Minimum Streamflow for Trout," University of Wyoming, Water Resources Research Institute, Series 37: 102 pp.

179. Whitford, L.A. and Schumacher, G.J. 1964. "Effect of Current on Respiration and Mineral Uptake in *Spirogyra* and *Oedogonium*," *Ecology*, 45: 168-170.

180. Wickett, W.P. 1954. "The Oxygen Supply to Salmon Eggs in Spawning Beds," Journal of the Fisheries Research Board of Canada, 15 (5): 1103-1126.

181. Wood, John. 1974. "Methods using flow related formulae - U.S. Bureau of Sport Fisheries and Wildlife," Fish and Wildlife Service Memorandum, Bureau of Sport Fisheries and Wildlife, Billings, Montana.

182. Wu, Y.F. 1931. "A Contribution to the Biology of Simulium (Diptera)," Papers of the Michigan Academy of Science, Arts, and Letters, 13: 543-599.

183. Zhadin, V.I. and Gerd, S.V. 1961. Flora and Fauna of the Rivers, Lakes, and Reservoirs of the U.S.S.R., Translated from Russian, Israel Program for Scientific Translations, Jerusalem, 1963. 626 pp.